The effect of different manual task simulation methods on hand and forearm demand estimates

by

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Abstract

The force exerted during manual tasks is a dominant risk factor for upper-limb musculoskeletal disorders. To identify tasks that may lead to fatigue over a shift, or increase the risk of injury, the demands placed on the hand and forearm system must be quantified and predicted. The purpose of this research was to determine how different ways of simulating manual tasks affected the estimate of demand on the hand and forearm and how well normative data could be used to provide an estimate of that demand.

The forces and moments required to perform 20 manual tasks were measured and simulations with three different levels of realism developed, ranging from simple feedback, with real parts, postures and timing to more controlled simulations with simplified parts, standard postures and 5s static exertions. 11 workers hired from a temporary employment agency each performed the simulated tasks and their physical demand was determined using perceived effort, the muscle activity of 8 hand and forearm muscles, and grip (or pinch) force matching.

Based on these criteria, the best simulation was that with the same handle size, shape and orientation as the criterion version of the task using simple feedback to match one or two forces. Over the variety of tasks studied here, perceived effort, grip force matching and extensor digitorum activation provided the most similar demand estimate to the criterion task of all measured parameters. The more controlled simulation had the highest correlation compared with normative demand.

Overall, the more changes in hand-object interface made between the task of interest and a simulation or normative data, the greater the discrepancy in demand. Normative data tended to underestimate demand, thus underestimating the risk of fatigue and injury. The use of simulations and task specific normative data to estimate hand task demand, with an accuracy useful for field measurements by ergonomists, was supported.

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Table of Contents

Appendices

List of Figures

List of Tables

1 Introduction

Manual tasks requiring repetition and force are associated with the development of musculoskeletal disorders (MSDs) of the upper limb (Silverstein et al., 1986, Moore & Garg 1995, Hagberg et al. 1995). In Ontario, between 1996 and 2004, MSDs resulted in over 27 million lost time days, and direct costs of $3.3 billion that reached $12 billion when indirect costs were included (Occupational Health and Safety Council of Ontario). In 2007 the cost of MSDs was 42% of all lost-time claim costs, including 889 lost-time claims for intervertebral herniated discs, 723 for carpal tunnel syndrome, 587 for epicondylitis, and 284 for rotator cuff syndrome (Ontario Ministry of Labour 2006, WSIB Annual Report 2007). According to the Bureau of Labor Statistics (2007), MSDs require some of the highest median days off work of all occupational illnesses and injures. For example, carpal tunnel syndrome required a median of 28 days off work, second only to fractures.

In order to identify tasks which may exceed the capability of parts of the population, may lead to fatigue over a shift, or increase the risk of injury, we need to assess the physical demands placed on the hand and forearm system. The force exerted during the execution of a task, modulated by its duration and frequency, is the dominant risk factor for upper-limb musculoskeletal disorders (MSDs) (Hagberg et al. 1995, Moore and Garg, 1995, National Research Council 2001, Silverstein et al. 2006, Thomsen et al. 2007). Therefore, the quantification and prediction of forces required for a task are important in designing sustainable work as well as in evaluating existing work.

The physical demand required by a manual task can be viewed in two ways. The external mechanical demand may be measured in N or Nm, for example a 50N insertion force. This is in contrast to the human demand required by a person performing the task in a given manner. For example using 70% of a mean maximum capability in a lateral pinch as reported in the literature, or a perceived exertion of 6 on a Borg CR-10 scale as the person is actually performing the task (Borg 1982, Koppelaar and Wells 2005).

If a manual task is simple, relevant normative data of demand may exist; a limited number of tables report the capability of percentiles of the population using a certain grip, in a certain posture, and applying force in a certain direction. These tables can be useful for estimating capability. But the use of normative data has limitations. Very frequently, manual strength is described as a grip force that may not match the known mechanical demands of the task. Wells and Greig (2001) and Greig and Wells (2004) have argued that the common approach of measuring grip force does not quantify the demand of complex, multi-axis hand exertions. In fact, the relationship between grip force and muscle activation was only moderate when the hand was used to transmit forces and moments to the environment rather than just gripping (Greig & Wells 2008). Normative data describing mechanical demands, such as a push or pull force, may be available for some general static situations, but changes in posture, and magnitudes or directions of forces may not be the same as the real task, meaning the task demand estimated using normative data will be poor. When applying normative data to situations that are different from that in which it was collected, the applicability to the task of interest must be questioned.

Simulating manual tasks is another method of estimating demand. Simulations can be complex, replicating all aspects of the task of interest or simpler, using a standard sized handle and visual feedback to match the forces required. For example, simulating radiator hose insertions in the laboratory facilitates the measurement of forces and muscle activity to help estimate task demand which would be more difficult to measure in a manufacturing environment.

The purpose of this research was to determine how different ways of simulating manual tasks affected estimates of physical demand on the hand and forearm and to determine how well normative data on hand capability estimated physical demand. A task that matched the assembly line task as closely as possible was developed. At the other extreme, the task was matched as closely as possible to how normative data would be collected. As Greig and Wells (2004) have published a comprehensive strength data set characterizing force and moment exertions along and about three axes, a simulation was matched to these conditions. Two further simulations bridged the change between these two extremes. Specifically the simulations were:

A. The realistic criterion task using the posture, timing, feedback and actual parts required to perform the real task as on the assembly line.

B. The most realistic simulation with a standard posture adjusted for each participant's height, 5s static exertions, simple feedback (1 or 2 forces) and real parts.

C. A simulation with standard posture adjusted for each participant's height, 5s static exertions, force and moment feedback (6 directions) and real parts.

D. The most controlled simulation with conditions similar to the normative data collections reported by Greig and Wells (2004), with standard posture adjusted for each participant's height, 5s static exertions, force and moment feedback (6 directions) and simplified parts.

Participants performed simulated tasks using real parts, or idealized shapes. They used either simple feedback to match one or two forces or moments or more complex feedback to match forces and moments in 6 directions. Hand and forearm demands were measured using perceived effort, grip force matching and the muscle activity of 8 hand and forearm muscles. The manual tasks examined were varied so as to include 4 grips, static and dynamic tasks, and varied direction and magnitude of force application.

Rationale: In order to identify manual tasks which may exceed the capability of segments of the population, may lead to fatigue over a shift, or increase the risk of injury, we need to assess the physical demand placed on the hand and forearm system. Simulating tasks in the laboratory allows the collection of detailed measures of demand. Varying types of simulations test the sensitivity of estimates of hand and forearm physical demand to changes in simulation methods.

1.1 Hypotheses

Three main hypotheses will be tested:

1. There will be no difference in estimated physical demand between the criterion task and the three other methods of simulating those tasks.
2. The rank order of tasks, according to the magnitude of parameters measured, will be the same for the criterion task and the simulations.
3. The physical demand determined using normative data will be the same as that determined using perceived effort and grip force matching during simulations.

2 Literature Review

2.1 *Measuring Demand*

The main goal of this research was to determine how three methods of simulating manual tasks affected the estimate of physical demand placed on the hand and forearm system compared to the criterion task and to determine how well normative data estimated demand. Figure 1 is an example of a manual task whose physical demand may be of interest due to its potential to lead to fatigue over a shift, or increase the risk of injury. This task requires the use of a pulp pinch to insert a wiper fluid nozzle into the hood of a car. The physical demand necessary to perform this task can be described in two main ways: the mechanical demand required to insert the nozzle determined by the forces and moments, and the human demand characterized by the perceived effort, grip strength matching and muscle activation.

2.1.1 Mechanical Demand

Mechanical demand is a characteristic of the task being examined. For the wiper fluid nozzle insertion, it is the forces and moments required to insert the nozzle into the car hood in some defined manner. Commonly, this is determined in automotive manufacturing plants using a hand-held force transducer but machine testing is also possible.

Machine testing involves the use of machines to measure forces or moments using a standardized method to ensure the procedure is repeatable. This method is often available only for specific situations. For example, an instrumented impact tester was developed specifically to measure the midsole hardness of running shoes using a standardized, accepted methodology (Clarke, Frederick & Cooper, 1983). Research participants wearing shoes that had a 50% difference in midsole hardness, as measured using machine testing, did not show a difference in vertical force impact peak when jumping on a force plate (Clarke, Frederick & Cooper, 1983). The body actively adjusted to differences in the shoe midsole hardness as shown by body kinematics (Frederick, 1986). While machine testing was useful for measuring midsole hardness using a standardized, repeatable met[illegible]easurements did not tell the whole story.

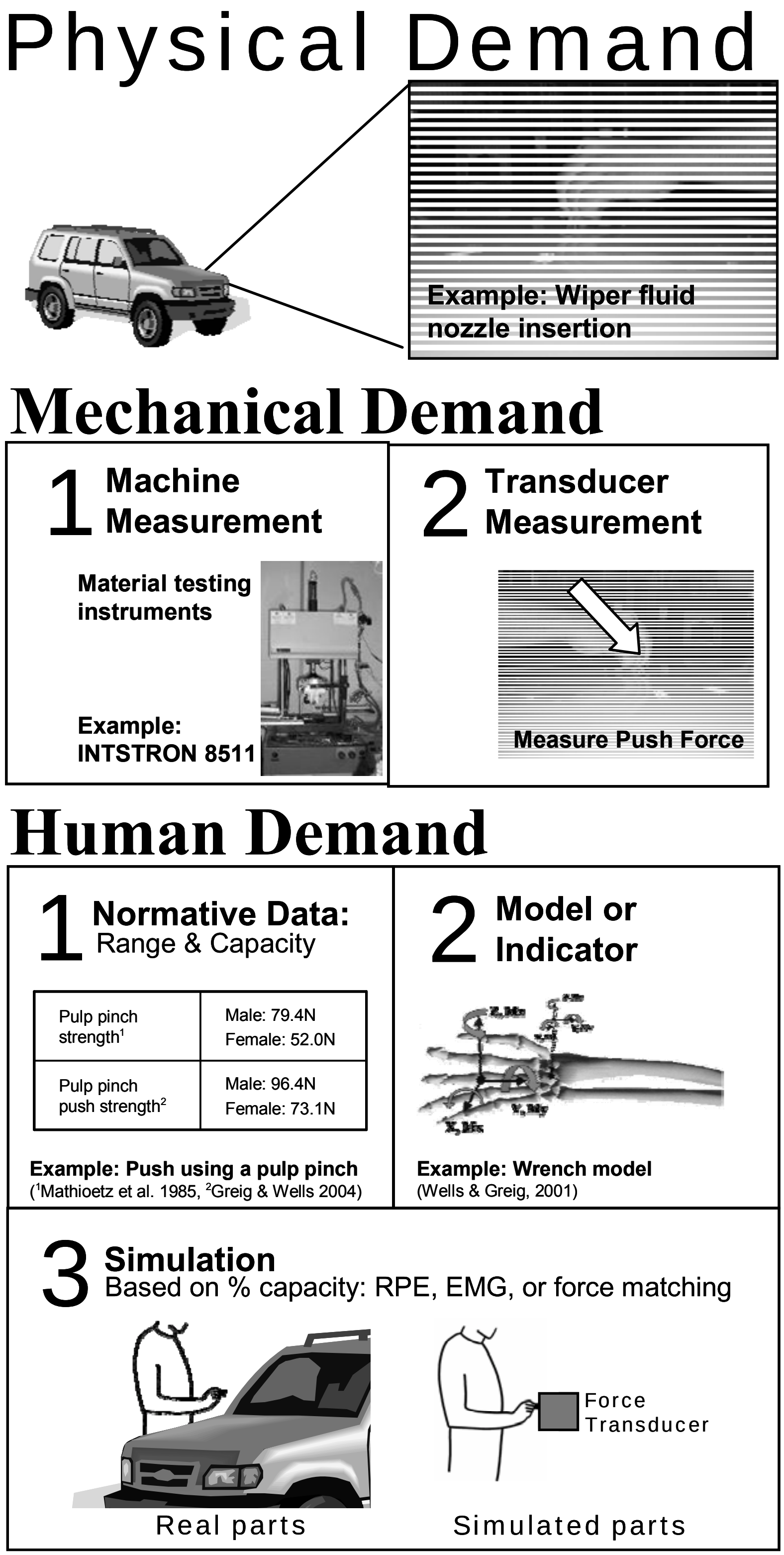


Figure 1: Example of a manual task found in the automotive industry to illustrate how physical task demand can be measured: wiper fluid nozzle insertion using pulp pinch

Considering the example of the wiper fluid nozzle insertion, it is unlikely that a standardized machine testing method using these parts and this direction of force application is available. In fact, due to the varied nature of tasks in an automotive assembly plant and the ever changing nature of the cars being made, there are very few tasks whose mechanical demand is determined using machine testing. More commonly, mechanical demand is determined using a hand held force transducer to measure the force requirements of a manual task (personal communication with J. Marshall, May 2009). This is done to ensure that forces are within the capabilities of the workers no matter what the manufacturer's machine testing values are. When a standardized method of using a hand-held transducer was developed, it was found to have no significant differences between forces determined using more sophisticated methods (Hoozemans et al. 2001). But situations in which standardized methods have been developed are rare. In most cases, the demand determined using a transducer is dependant on the way the force is applied and its speed of application (Stephens & Vitek, 1998). For example, hand held force transducers have been used to measure the unidirectional radiator hose insertion force. To do this, a section of the hose was cut and a force transducer was used to push it onto the phalange of the radiator. In the actual manufacturing setting, slightly different methods may be used to insert the hose, turning or wiggling has been shown to decrease the insertion force (Grieshaber & Armstrong, 2007). The hose insertion process is variable and dependant on the method of insertion used (Drinkhaus et al., 2009). For the wiper fluid nozzle insertion example, measuring the insertion force is dependant on similar factors. Wiggling or twisting the nozzle during insertion may affect the insertion force and the resulting demand. While the use of transducers helps to obtain a general idea of mechanical demand, it is affected by the method used and is only an indication of the mechanical demand required; it may not predict the task's physical demand well.

Take home message: Mechanical demand is one component of physical task demand. It can be determined by machine testing or hand held transducer measurement. Demand determined using these methods may not predict the human demand well and may subsequently misrepresent the physical demand of a task.

2.1.2 Human Demand

Some measure of human demand is necessary to determine a person's ability to perform a manual task. Human demand can be estimated using tabulated values of human range and capability, models and manual task simulations.

Tables of normative data have been collected to show the range or capacity of a certain population. For example, many authors have published grip and pinch strength values showing that greater grip strength can be achieved using a power grip compared to a pulp pinch:

- Power grip: 451 N (Greig & Wells 2004), 528 N (Mathiowetz et al. 1985 (1), smaller handle diameter), 382 N (Mital & Kumar 1998), 429 N (this research)
- Pulp pinch: 107 N (Greig & Wells 2004), 114 N (Mital & Kumar 1998), 113 N (this research)

However, the mechanical demands of activities are often expressed in terms of external forces and moments, not grip or pinch forces alone, and much less of this type of normative information is available.

- Push using a power grip: 114 N (Greig & Wells 2004), 112 N (Seo et al. 2008)
- Push using a pulp pinch: 96 N (Greig & Wells 2004), 53.6 N (Potvin et al. 2006)

This normative data shows that greater push strength can be achieved using a power grip compared to a pulp pinch. Applying this information to the wiper fluid nozzle insertion example, a higher push force would be acceptable to more people if a power grip were required rather then a pinch grip. But the dynamic wiper fluid nozzle insertion is different from the situation in which the normative data was collected. The size and shape of the wiper fluid nozzle requires the use of a pulp pinch, limiting push force to a maximum of 96N in a male population. While normative data gives the idea that a power grip might make this task easier, the characteristics of the task itself suggest that a pinch grip is required.

Other issues regarding the use of normative data are the population from which the data was obtained and its availability. Normative data from male populations may not apply to a female population of workers whose grip and push strength may be lower (Kumar, Narayan & Bacchus, 1995). If available, normative data may not be applicable to situations different from that in which it was collected, and its transferability back to the task of interest must be ensured. The use of range and capacity tabulated data is an approximation of human demand that may not always be applicable to the particular task of interest.

Development and validation of models used to estimate human demand may be time consuming but models have the potential to increase the speed with which demand can be estimated. For example, muscle activation has been used to estimate grip and pinch force under standardized conditions. Measuring grip strength in the field is difficult due to time and equipment demands (Keir & Mogk 2005, Kopelaar & Wells 2005). For the wiper fluid nozzle insertion example, measuring the pinch force would require instrumenting a wiper fluid nozzle, not easy or inexpensive. Keir and Mogk (2005) used the muscle activation of 6 finger and wrist muscles to model grip strength. They found that muscle activation explained 85% of the variance in grip force in a standardized grip in similar postures. This model can estimate grip force and does not require instrumenting parts, but is limited to situations where multiple EMG signals can be recorded and processed and in which external forces and moments are not applied. The muscle activation may in fact be a better measure of demand than the modeled force.

Another indicator of human demand that does not require instrumenting parts or recording EMG is perceived effort. The Rating of Perceived Exertion, (CR-10) for example, has been used to estimate local effort (Borg 1982). Such a measure is considered an estimate of human demand that takes into consideration factors that may not be measured using mechanical measures, such as demand in muscles that are not being monitored. Self-rating mechanical exposure may estimate an exposure that is adequate for some cases (Petersson et al. 2000). Kopelaar & Wells (2005) found good precision and reliability when comparing perceived exertion with effort determined using other methods such as electromyography (EMG). However Bao et al. (2006) noted a weak correlation between directly measured pinch and power grip force and participant's self-reported force levels. While perceived exertion can be an indicator of human demand, it has been found to be a poor measure in some studies.

Force matching is another indicator of human demand that requires people to estimate the force or moment necessary to complete a task without instrumenting parts. Force matching for the wiper nozzle insertion example would require participants to insert the nozzle into a car hood and then use the same grip to press against a force transducer with their estimation of the same force. Wiktorin et al. (1996) found that people could reproduce magnitudes of push and pull forces in one direction fairly well but had difficulty quantifying the magnitude of these forces. Sometimes only a weak correlation between workers' self-reports and measured grip forces can be found (Bao & Silverstein 2005, McGorry, Depmsey and Casey 2004). Force matching can be used to estimate human demand but requires caution in its application.

The human demand required to perform a task can also be estimated by simulating a task and taking measures of demand while participants perform this simulated task. Researchers simulate tasks in the laboratory to facilitate the measurement of task demands, EMG collection, posture and forces. Kopelaar & Wells (2005) used simulations of tasks of everyday living to compare methods of determining task demand. For example, a plate was instrumented to measure pinch force. The changes made to the task to measure pinch force make this task representative of holding a real plate, but unless this is compared to a real plate hold, we do not know how good an estimate it is. Cort et al. (2006) simulated fastener initiations in the laboratory, a task that may lead to injury. To simulate the task, researchers constructed an instrumented, height adjustable fastener initiation apparatus and determined guidelines about the rate of fastener initiations that would be acceptable to 75% of female participants. These guidelines, developed in the laboratory, might not transfer well to a real work situation. Differences in the work environment and the worker population may mean this rate is slower, or faster than that preferred by real workers. Demand estimated using a simulation is often a choice of researchers interested in a specific task to facilitate measurement. When simulating tasks, the transferability of data to the real task can be questioned, the human demand measured using a simulation may be a poor estimate of the demand required to complete the actual task.

Take home message: Human demand can be estimated using normative data, models, perceived exertion, force matching and simulations. Each method is subject to limitations that must be considered when applying demand estimates to real tasks.

Understanding physical demand requires understanding two parts. The mechanical demand required to perform a task can be determined using mechanical testing if standardized testing procedures are available, or transducer measurement. The human demand required to perform a task can be estimated with tabulated normative data, models, indicators or simulations. If the human demand required to perform a task is underestimated, it has the potential to result in tasks that cause fatigue over a shift and increase the risk of injury. The mechanical and human demand placed on the hand and forearm system together can help to measure exertion and identify tasks that may lead to fatigue over a shift, or increase the risk of injury.

Take home message: Physical demand consists of both mechanical and human components. Simulations help to measure demand and identify MSD risk but the method of simulating a manual task may affect demand measurement.

2.2 Normative data

Normative data is obtained by taking measures on multiple people to determine the distribution of strength of that population. It can be used to determine the effectiveness of a surgical procedure by comparing the grip strength of a patient after surgery with that of a related normative population (Mathiowetz et al., 1985(1)). Normative data is also useful for estimating human demand for a specific task. Tasks requiring higher forces and moments require a higher percentage of the normative strength of the population and are more likely to lead to fatigue over a shift and increase the risk of injury.

Caution must be used when applying normative data to a specific situation. Normative data is itself subject to limitations and the situation in which the normative data was collected may be different from that in which it is being applied. For example, using normative data to estimate the demand of manual tasks with a different handle size, or posture from that used to collect the normative data may result in an inaccurate demand estimate.

Normative data is commonly available for maximum pinch and grip strengths. Manual tasks that require a grip along with the application of a force or moment have more limited normative data. Greig & Wells (2004) published the normative strength data of a population of 10 males recruited from an industrial temporary employment agency. This data is unique in that it considers the application of forces and moments in 6 directions for 3 grips. Most other normative data found, was determined for a specific purpose so that only forces or moments in one or two directions were obtained.

Normative data is available for a single direction of force or moment application or grip strength. Tasks with combinations end up with normative demand based on one component. Seo et al. (2008) measured the inward and outward torque and axial push force of the hand gripping a handle using a diagonal volar grip; Ciriello et al. (2002) measured the maximal acceptable torques during screw driving with a diagonal volar grip, and the maximal ulnar deviator moment using a power grip; Potvin et al. (2006) determined the maximal acceptable forces for repeated manual insertions using a pulp pinch and a diagonal volar grip; Kong et al. (2007) investigated torque during a screw driving task using a diagonal volar grip; Mathiowetz et al. (1985(1)) measured normative pinch and grip strength for adults; Seo (2009) examined the relationship between the force generated using a lateral pinch and the pinch force; Adams & Petersson (1988) investigated the maximum torque generated when tightening connectors using a lateral pinch; Peebles & Norris (2003) published up to date strength data; and Haslegrave et al. (1997) looked at hand and forearm strength capabilities while kneeling. This data is shown in Table 1.

Table 1: Normative grip and pinch data with the forces and moments that can be applied in that grip

	Grip (N)	Push/ Pull (N)	Dorsal/ Palmer (N)	Radial/ Ulnar (N)	Pronation/ Supination (Nm)	Radial/ Ulnar Deviator (Nm)	Extensor/ Flexor (Nm)
Power Grip	290.1.±63.3[1] 222±87[2] 49.90±9.60[9]*	**Push:** 113.6±31.6[1] 112±27[2] 471.62±208.03[9]* 282±117[10] **Pull:** 113.6±19.3[1]	**Dorsal:** 74.4±17.2[1] 167±95[10] **Palmer:** 87.1±15.0[1] 151±61[10]	**Radial:** 194.6±49.1[1] 203±104[10] **Ulnar:** 161.2±48.3[1] 308±137[10]	**Pronation** 8.1±2.3[1] **Supination:** 8.0±1.9[1] 33.6±9.2[9]	**Radial Dev.:** 10.3±3.5[1] **Ulnar Dev.:** 13.0±4.2[1] 6.55±0.29[3]	**Extensors:** 2±1.7[1] **Flexors:** 9.3±2.0[1]
Diagonal Volar Grip		**Push:** 104.0±16.7[4]			**Pronation:** 6.9±1.3[2] 2.39±0.29[3] 5.73[5] **Supination:** 5.1±1.2[2] 3.02±0.35[3]		
Lateral Pinch	89.1±13.3[1] 109.4±21.0[6]	**Push:** 104.9±21.1[1] 96±36[7] **Pull:** 96.6±21.2[1]	**Dorsal:** 56.0[1] **Palmar:** 57.8[1]	**Ulnar:** 70.9±12.3[1]	**Pronation:** 3.8±1.1[1] 1.26[8] **Supination:** 3.5±0.8[1] 1.29[8]	**Radial Dev.:** 3.0±1.1[1] **Ulnar Dev.:** 1.7±0.5[1]	**Extensor:** 1.3±0.6[1] **Flexor:** 0.9±0.3[1]
Pulp Pinch	107.3±27.6[1] 75.6±18.0[6]	**Push:** 96.4±19.0[1] 53.6±8.8[4] **Pull:** 100.2±23.9[1] 75.52±29.3[9]	**Dorsal:** 44.0±10.3[1] **Palmer:** 42.2±1.7[1]	**Radial:** 101.9±11.7[1] **Ulnar:** 75.1±17.4[1]	**Pronation:** 2.2±0.4[1] **Supination:** 2.4±0.8[1]	**Radial Dev.:** 1.7±0.3[1] **Ulnar Dev.:** 2.6±0.9[1]	**Extensor:** 2.1±0.6[1] **Flexor:** 2.6±0.8[1]

*Differences in the magnitude may be due to multiple factors including different dynamometers, handles sizes, populations, testing protocols.
1. Greig & Wells (2004); 2. Seo et al. (2008); 3. Ciriello et al. (2002); 4. Potvin et al. (2006); 5. Kong et al. (2007): Investigated torque during a screw driving task using a diagonal volar grip.
6. Mathiowetz et al. (1985(1)); 7. Seo (2009); 8. Adams & Petersson (1988); 9. Peebles & Norris (2003); 10.Haslegrave et al. (1997)

In this research, normative data and the mechanical demand of the task was used to determine the demand required to perform a manual task and its simulations. This was compared with the demand measured while participants performed the task. The purpose of this comparison was to determine how well normative demand compared to that measured while participants were performing a task.

Take home message: Normative grip strength data is common, that for the application of forces and moments in specific directions is more limited. Complex tasks do not have normative data

2.3 Differences between simulations and their potential consequences

This research involved simulating 20 manual tasks using four methods to determine how different ways of simulating manual tasks affected estimates of physical demand on the hand and forearm system and also to determine how well normative data estimated physical demand. Understanding the potential differences between a highly realistic version of a task and its simpler simulations is useful for determining the potential consequences of simulating manual tasks with different levels of fidelity. For example, a complex simulation in the laboratory involving real parts, real postures and real timing is more like the highly realistic version of a task than a simulation with a 35mm cylindrical handle, a standard static posture and set timing. A list of possible sources of differences between the most realistic version of a task and its simulations is included in Table 2.

Table 2: Differences between simulations and their potential consequences

Difference	Description
Dynamic vs static	▪ The most realistic version of some tasks involved dynamic activities. For example, inserting the radiator hose was a dynamic task compared with this task's static simulations. ▪ Motion magnifies concerns with electromyographic measurement. Dynamic tasks may cause the distance between the active muscle fibres and the electrodes to change. As the electrodes on the skin move, spatial filtering may alter the signal frequency, or bring the electrodes into the territory of a new active motor unit. The non-linear variation of the force-length relationship of muscle fibres may change the shape of the motor unit action potential (DeLuca, 1997). ▪ During fast wrist flexion, Werremeyer and Cole (1999) noted a significant increase in grip force. They also noted that slow production of isometric wrist force allowed participants to regulate their grip strength and stop it from increasing drastically. ▪ The applied force changes throughout a dynamic task and may cause differences in muscle activation that do not exist in static task simulations (Mital & Kumar 1998, Maier & Hepp-Reymond, 1995) ▪ Dynamic tasks may yield changes in muscle activation, grip force and the applied force compared to static simulations.
Changes in posture	▪ The most realistic version of a task involved the actual posture used when performing that task. ▪ Any simulations of this task involved a standard posture with participants standing with their feet shoulder width apart, their right arm against their side with their shoulder in 0º of abduction and 0º of flexion, elbow bent to 90º, gripping the height-adjusted handle. ▪ Changes in wrist posture may have affected the estimated grip and pinch force. For example Mogk and Keir (2003) found a lower grip force with a flexed wrist posture (213N) compared to a neutral posture (393N) or an extended posture (386N). Pryce (1980) also found lower grip strength in flexion combined with ulnar deviation and lower grip strength in ulnar deviation when the wrist was extended. ▪ Adams and Peterson (1988) noted a higher torque

Difference	Description
	generated using a pulp pinch in a flexed posture (1.98Nm) compared to a neutral posture (1.65Nm). These researchers also noted a decrease in grip strength from a supinated posture (247N) to a pronated posture (183N) but no significant differences in grip strength with either radial or ulanr deviation compared to a neutral posture. ▪ Imrhan (1991) found that a lateral pinch in radial deviation was stronger than one in extension, neither different from pinch strength with ulnar deviation. ▪ Changes in elbow posture may affect grip and pinch strength as well. Several researchers have noted an increased grip strength with a fully extended elbow compared to a flexed elbow (Kuzala & Vargo 1992, Mathioweitz et al. 1985(2), Oxford 2000, Su et al. 1994). ▪ Changes in shoulder posture may affect the measured task demand. For example, overhead postures are associated with higher muscle activity (Su et al., 1994, Sporrong, Palmerud & Herberts, 1995) ▪ Postural changes may also be quantified by looking at different task heights. Ulin et al. (1993) noted that work height affected perceived effort as measured using the Borg 10-point scale. Waist height work (64cm from the floor) was rated with a 6.0. At eye level (114cm from the floor) this decreased to 3.6 while above head level (165cm from the floor) this increased to 5.2. These researchers also noted that horizontal distance from body affected perceived effort. A horizontal distance of 13cm had an average rating of 3.6. A distance of 63cm had an average rating of 5.1 (Ulin et al. 1993). ▪ Similarly, Ortengren et al. (1991) noted an increase in muscle activation with higher work height. This was associated with an increase in trapezius muscle activity, 25%MVE at waist height, 45%MVE at eye height and 62%MVE above the head. ▪ Changes in task height and posture may cause differences in muscle activation, perceived effort and grip force between the most realistic version of a task with a real posture and its simulations with standard postures.

Difference	Description
Changes in object size	▪ The size of the handle used for tasks with real parts may have been either larger or smaller than that of the simulations. ▪ Changes in handle size have been associated with changes in grip strength by many researchers. Several have reported that maximum grip strength was obtained with a handle diameter near 50mm (Fransson & Winkel, 1991, Oh & Radwin, 1993). Alternatively, Kong & Lowe (2005) reported that the handle diameter that enables the highest maximum grip is related to hand size. ▪ As well as affecting power grip strength, handle size is also associated with changes in pinch strength. Higher pinch strength was sustained with a 50mm handle (54N) compared to either a 30mm handle (51N) or a 70mm handle (48N) (Dempsey & Ayoub, 1996). Maximum pinch strength has also been related to hand size (Shivers, Mirka & Kaber, 2002). ▪ The amount of torque that can be applied to a handle has been found to increase as the handle size increases (Cochran & Riley, 1986, Kohl, 1983). ▪ Changes in handle size affect the maximum grip and pinch force, impacting on grip and pinch force estimates.
Changes in object shape	▪ The shape of the handle used for tasks with real parts was different than the simplified parts used for some of the simulations. ▪ With the elbow bent at 90º and the forearm parallel to the ground, higher push and pull forces were generated for cylindrical handles followed by cylindrical handles with flat sides, than rectangular and triangular handles (Cochran & Riley, 1986) ▪ Triangular knobs were found to allow for more torque generation than knobs with more sides (square, rectangular, circular) (Kohl, 1981). ▪ Changes in handle shape may cause changes in a participants ability to generate force and torque.

Difference	Description
Changes in object material	▪ The handle for tasks with real parts was often different than the sport-tape covered handles used for simulations with simplified parts. ▪ Higher friction between the hand and the handle is associated with higher pinch forces and higher maximum torque generation (Cadoret & Smith 1996, Seo et al., 2008) ▪ A change in handle material may cause changes in task demand by changing the friction between the hand and the handle.
Changes in object orientation	▪ The handle orientation between the most realistic version of a task and its simplified simulations was different for several tasks. ▪ A diagonal volar grip using a horizontal handle, was associated with an average increase in forearm muscle activity of 57-95% compared to a vertical handle (Fischer, Wells & Dickerson, 2009). ▪ Changes in handle orientation may contribute to changes in estimated demand.
Vibration	▪ Vibration has been shown to increase finger flexor activity by up to 6 times with vibration at 1000Hz and to increase extensor muscle activity by 32% compared to a static condition (Gurram, Raheja & Gouw 1995, Radwin, Armstrong & Chaffin 1987) ▪ Grip force has also been shown to increase with vibrations of increasing frequency. For example, Radwin, Armstrong & Chaffin (1987) reported a grip force of 25N for a static hold, increasing to 32N with vibrations of 40Hz. ▪ Vibration during the criterion drill push & turn tasks, may have increased muscle activity and estimated grip force compared to the static simulations.
Force control vs. posture control	▪ The most realistic version of some tasks used posture control while all task simulations used force control. ▪ Force control has been associated with 3-4% higher middle deltoid activity than similar posture controlled exertions (Au & Keir, 2007). ▪ However, larger fatigue development and higher perceived effort (on a 10-point scale) has been associated with posture feedback (6.5) compared to force feedback (4.5) (Sjogaard

Difference	Description
	et al., 2000). ▪ Posture controlled tasks may have slightly lower muscle activation and higher perceived effort compared to their force controlled simulations.
Changes in mental demand	▪ Performing tasks with simple feedback (force feedback in a maximum of 2 directions) had a different mental demand than performing tasks with force and moment feedback in 6 directions. ▪ Au & Keir (2005) included a mental task during a maximal grip exertion and found this reduced the magnitude by 7%MVC. Including a shoulder exertion reduced the grip magnitude by 10%MVC. ▪ The increased mental demand of task simulations with 6 directions of force and moment feedback may be a source of demand differences between criterion task, and simulations.
Changes in grip types: Hybrid grips	▪ Some tasks required a grip or pinch that was clearly defined, others required a hybrid grip and pinch. ▪ For example, the wire harness connector required a lateral pinch with power grip to accommodate the wires protruding from the rear of the connector. ▪ The wires are another point of connection between the hand and the wire harness, allowing force to be transferred to the connector from the palm of the hand due to the power grip, as well as the fingers due to the lateral pinch. ▪ The use of hybrid grips for the most realistic version of a task compared to clearly defined grips for simulations may be a source of differences in demand.
Obstructions	▪ The most realistic version of a task was done with real parts. In some cases, for example the radiator hose insertion, this included obstructions to hose insertion that did not exist for simulations. ▪ Griehaber, Lau & Armstrong (2007) found that the force and posture required to insert a hose was rated as “more difficult” for obstructed tasks compared to unobstructed tasks. ▪ Obstructions in the most realistic version of a task may have caused differences in demand estimates between the most

Difference	Description
	realistic version of a task and its simulations.
Changes in the degrees of freedom	▪ The most realistic version of hose insertions and wire harness connectors were dynamic tasks. ▪ As the parts were being connected, the degrees of freedom allowed for force and moment application decreased. ▪ For example, when the radiator hose was initially being pushed onto the phalange of the radiator, it could be rocked back and forth. As it was inserted farther onto the phalange, this rocking motion had to decrease. ▪ This change in the number of degrees of freedom may be a source of the differences in muscle activation between the most realistic version of this task and its simulations (Fischer et al. 2009).
Changes in the Task over Time	▪ For some tasks, mechanical demand changes as the task is performed multiple times. ▪ For example, inserting a radiator hose the first time was more difficult because rubber has a higher stiffness when it is stretched more than it has previously been stretched (Brown 2006). Repeated stretching causes a much smaller effect as the physical breakdown of the rubber composite eventually reaches some equilibrium (Brown 2006). ▪ Similarly, for plastic wire harness connectors, the viscoelastic behaviour of the polymer means that plastic can be deformed during the first connection and may never return to its original shape (Askeland 1994). This again implies that a connector may require a higher insertion force initially than for subsequent insertions. ▪ To maintain a constant connection force over all participants, the connectors were mechanically conditioned , exercised, so that the insertion forces were constant. This allowed the simulations to proceed with a minimal number of parts, rather than using a new part for each insertion. ▪ The demand, when actually inserting a new part will be higher than a simulation based on a pre-stressed part.

2.4 Simulation Explanation

Simulations of the 20 manual tasks were developed to range from the extremely real criterion task that closely matched the assembly line task to a more controlled simulations, resembling the normative data methods of Greig and Wells (2004). Two intermediate steps between these two end points were chosen to bridge the gap. An example task with explanations of differences between the criterion task and each simulation is included below in Table 3.

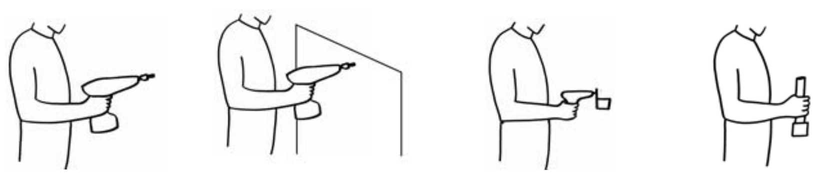
A. The realistic criterion task using the posture, timing, feedback and actual parts required to perform the real task as on the assembly line.

B. The most realistic simulation with a standard posture adjusted for each participant's height, 5s static exertions, simple feedback (1 or 2 forces) and real parts.

C. A simulation with standard posture adjusted for each participant's height, 5s static exertions, force and moment feedback (6 directions) and real parts.

D. The most controlled simulation with conditions similar to the normative data collections reported by Greig and Wells (2004), with standard posture adjusted for each participant's height, 5s static exertions, force and moment feedback (6 directions) and simplified parts.

Table 3: Example of differences between the criterion task and each of the simulations



	Criterion Task A	Simulations B	Simulation C	Simulation D
Posture	Real task posture	Standard posture, adjusted for participants height (elbow at 90º, 0º should abduction)		
Timing	Real task timing	5s static exertions		
Feedback	Real task feedback	Simple feedback (1 or 2 forces)	Force and moment feedback (3 forces & 3 moments)	
Parts	Real parts			Simplified parts
Realism	Most realistic			Most controlled

3 Methodology

This section covers details on the methodology used, including details about the participant population, a description of each manual task examined, and the procedures used to estimate demand. The procedures section includes details on equipment including measurement of grip and pinch forces, applied forces and moments, electromyography, eliciting maximal muscle activation, posture, perceived exertion and data collection.

The experimental design is also discussed including the statistical analyses used to compare simulations within and between the different manual tasks and their simulations.

3.1 Participant Population

12 right-hand dominant male participants (Table 4) with industrial manual work experience were recruited from a temporary industrial employment agency. One participant was unable to complete the study and this data was not considered in the analysis. All participants were free of injuries to their hand and forearm in the last 6 months, were free of pain on the day of testing and free of chronic hand and forearm pain. Informed consent was obtained prior to the start of the study and this procedure was approved by the Office of Research Ethics, University of Waterloo.

Table 4: Average participant information

	Average ± Standard Deviation
Age (years)	28 ± 9
Weight (kg)	83 ± 16
Height (cm)	179.2 ± 6.1
Max grip (N) *Using Jamar dynamometer on 2nd grip setting	429 ± 71

3.2 Task Choices

The majority of tasks were chosen from those on an automotive assembly line. These included tasks that had recently been redesigned or were being considered for redesign due to concerns and tasks with no known concerns. Tasks were selected to include a wide variety of grasps. Tasks chosen generally had lower force and moment requirements due to their repetitive nature. To test whether simulations and normative data estimated higher demands well, a second version of some of these tasks was developed with higher force and moment requirements. As well, some tasks of every day living were included to ensure at least 5 tasks per grip were studied that were both static and dynamic, requiring the application of forces in moments in different directions. A summary of task information can be found in Table 5. Additional details regarding these tasks can be found in Appendix A.

For the 20 manual tasks chosen, 6 manual tasks had 4 types of simulations plus the criterion task, 14 manual tasks had 3 types of simulations plus the criterion task for a total of 86 tasks. Each task was performed once. Ten random tasks were repeated at the end of the protocol (i.e. different tasks for each participant).

Table 5: Description of tasks

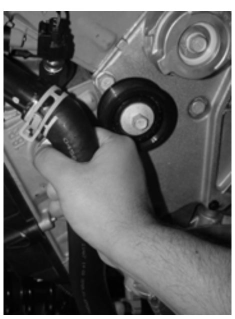
Hammer Holds

(Appendix A: Tasks 1, 2, 3 & 4)

- **Task Type:** Static
- **Grip:** Diagonal volar grip
- **Similar Tasks:** Requires a radial deviator moment, common to many tasks of every day living. Similar actions used by workers on an automotive assembly line using a rubber mallet to ensure trim is attached flush to a surface. While waiting for the next car to come down the assembly line, workers hold the mallet in a posture similar to this. Holding a frying pan has similar demand but a different wrist posture.
- **Task Variation:** Force and moment magnitude was varied by using different sized hammers
  - 22oz hammer (Task 1)
  - 16oz hammer (Task 2)
  - Sledge hammer (Task 3)
  - Modified heavy hammer (additional weight added to a 22oz hammer, Task 4)
- **Required Forces & Moments:** Forces and moments were determined for each hammer using the mass and the distance from the centre of mass to the grip centre
  - Participants matched a radial deviator moment and a vertical force (1 non-zero force, 1 non-zero moment)

Hose Insertions

(Appendix A: Tasks 5, 18)



- **Task Type:** Dynamic
- **Grip:** Diagonal volar grip
- **Similar Tasks:** Similar actions seen in hose insertions in other industries. This task has been associated with a high peak force rating when compared to other tasks in an automotive assembly plant (Ebersole & Armstrong, 2004)
- **Task Variation:** The insertion force of the exercised hoses and grip were varied by using different sized hoses
  - Radiator hose - diagonal volar grip (Task 5)
  - Power steering hose - modified lateral pinch (Task 18)
- **Required Forces & Moments:** Forces were determined using the mass of the hose and the average insertion force measured using a force transducer.
  - Participants matched the push force and the vertical force (2 non-zero forces)

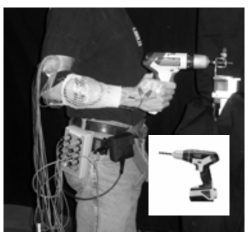
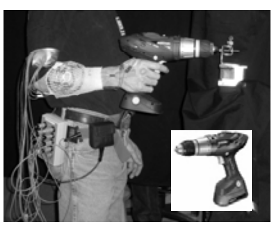
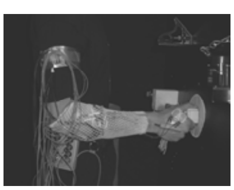
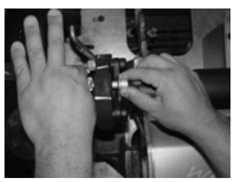
Window seal insertion using “pizza wheel” **(Appendix A: Task 6)** 	▪ **Task Type:** Dynamic ▪ **Grip:** Power grip ▪ **Similar Tasks:** Similar actions seen in painting a ceiling with a brush or roller. ▪ **Required Forces & Moments:** Forces and moments were applied in 2 directions. Forces were determined using the mass of the pizza wheel and the average forces required to insert the window seal. o Participants matched an upward and dorsal force (2 non-zero forces)
Large and small drills **(Appendix A: Tasks 7, 8, 9, 10, 11 & 12)** Small Drill  Large Drill 	▪ **Task Type:** Static and Dynamic ▪ **Grip:** Power grip ▪ **Similar Tasks:** Similar actions seen in the use of many pistol grip power tools. ▪ **Task Variation:** A range of forces was obtained by using two different drills o Large drill mass: 2.36kg (Tasks 7, 8, 9) o Small drill mass 0.75kg (Tasks, 10, 11, 12) ▪ **Required Forces & Moments:** The three tasks for each drill had an increasing number of forces and moment greater than zero that had to be matched. Forces and moments were determined using the mass of the drills, the average maximum torque generated by the drill and an estimate of the push force. o Hold: Participants matched a vertical force (1 non-zero force, Tasks 7 and 10) o Push: Participants matched a vertical force and a push force (2 non-zero forces, Tasks 8 and 11) o Push & torque: Participants matched a vertical force, a push force and a pronator moment (2 non-zero forces, 1 non-zero moment, tasks 9 and 12)
Wire harness connections **(Appendix A: Tasks 13 & 14)** 	▪ **Task Type:** Dynamic ▪ **Grip:** Lateral pinch o The connector with wires is the most realistic but required a modified lateral pinch to accommodate the wires protruding from the rear of the connector (Task 13). The connector without wires required a lateral pinch without modification (Task 14). ▪ **Similar Tasks:** Similar actions seen in other connectors in the automotive industry that require a push force. ▪ **Required Forces & Moments:** The average insertion force of exercised connectors was determined using a force gauge. o Participants matched a push force (1 non-zero force)

Plate hold 0.5kg and 2.2kg
(Appendix A: Tasks 15 & 16)

	▪ **Task Type:** Static
	▪ **Grip:** Lateral pinch
	▪ **Similar Tasks:** Similar actions used when holding a book or other object.
	▪ **Task Variation:** Two different masses were used
	    o Task 15: 0.5kg mass reflects the weight of food on a plate
	    o Task 16: 2.2kg mass reflects the mass required to generate a radial deviator moment of 70%MVC for the average female (Greig & Wells 2004)
	▪ **Required Forces & Moments:** Forces and moments were determined using the mass of a meal and 70% of the maximum radial deviator moment capabilities of the average woman.
	    o Participants matched a vertical force and a radial deviator moment (1 non-zero force, 1 non-zero moment)

Nut turn
(Appendix A: Tasks 17 & 19)

	▪ **Task Type:** Dynamic
	▪ **Grip:** Pulp pinch
	▪ **Similar Tasks & Variation:** Similar actions seen in many industries and situations.
	▪ **Required Forces & Moments:** Forces and moments were determined using the average push force and torque required to turn a nut on a bolt wrapped with 6cm of Teflon tape.
	    o Task 17 Extended posture: Participants matched a push force and a supinator moment (1 non-zero force, 1 non-zero moment)
	    o Task 18 Neutral posture: Participants matched a push force and an ulnar moment (1 non-zero force, 1 non-zero moment)

Brake line cap removal **(Appendix A: Task 20)** 	▪ **Task Type:** Dynamic ▪ **Grip:** Pulp pinch ▪ **Similar Tasks:** Similar actions are seen in many industries and situations. ▪ **Required Forces & Moments:** The average removal force was determined using a force gauge when pulling exercised caps off of a brake line. o Participants matched an upward force (1 non-zero force)

3.3 Procedures

Tasks were presented in random order to participants. The criterion tasks required postures dictated by the task that were not adjusted for each participant, for example, the window seal insertion using the 'pizza wheel' required participants to work above shoulder height. For simulations C and D, participants were positioned in front of the height adjusted tasks with their feet shoulder width apart, elbow flexed to 90º, and shoulder in 0º abduction. Participants practiced each task until they felt comfortable and the experimenter was confident they could perform the task in a consistent, repeatable manner. For example, when inserting the radiator hose, participants practiced until they could push the hose straight onto the phalange of the radiator at a moderate speed. For tasks with visual force and moment feedback, participants practiced until they could apply the required forces and moments within ±10% of the target. For most tasks, this practice lasted approximately 30s. After participants felt comfortable with a task, they rested for approximately 30s, or longer if they had been practicing a task requiring high forces or moments, before they performed the task one last time and data was collected. In some cases, even after practice when participants repeatedly could not meet the task force and moment targets, the participant's best effort was used. Participants then rated their perceived effort and gripped or pinched a grip or pinch gauge with as much force as they felt they used during the task.

3.4 Equipment

A block diagram of the equipment used can be found in Appendix B.

3.4.1 Grip & Pinch Force

A strain gauge dynamometer (dynamometer) with signal conditioner was used to measure diagonal volar grip force (MIE Medical Research Ltd., Leeds, UK and Daytronic 3270 Strain Gauge Conditioner, A-Tech Instruments Ltd., Scarborough, Canada). Additionally power grip forces were measured using a Jamar dynamometer (Jamar model 2A). Pinch force, both lateral and pulp, were measured using, a pinch gauge (Model PG-60, B&L Engineering, Tustin, USA) and the same dynamometer mentioned above.

The dynamometer was adapted for power grips and diagonal volar grips with two round shells covered in white athletic tape, attached to the arms, increasing its diameter to 6cm. For lateral and pulp pinches, two plates 2.6cm wide covered in athletic tape were attached to the ends of the arms of the dynamometer to provide enough area to comfortably pinch. The dynamometer was calibrated using the shunt calibration values. Prior to testing, the shunt calibration was verified. The Jamar hand grip dynamometer (Jamar) was set to the 2nd grip setting, the position of maximum power grip strength for 61% of participants according to Crosby, Wehbé & Mawr (1994).

Maximum grip and pinch strength were measured using each of the instruments as listed in Table 6. For these trials, participants were seated with their forearm resting on an armrest at approximately 90º to their upper arm. During the 5s collection, participants were asked to gradually ramp up to their maximum grip or pinch strength. At least 2 maximum grip or pinch trials were collected for each measurement device in each grip. If the difference between the two was greater than 10%, a third trial was collected. The maximum grip or pinch strength determined using the appropriate pinch or grip gauge, Jamar dynamometer for a power grip, strain gauge dynamometer for the diagonal volar grip and the pinch gauge for the lateral and pulp inch, was used to normalize the grip or pinch force (%MVC).

Table 6: Grip and pinch maximums were measured with different methods

Power grip maximum	Diagonal volar grip maximum	Lateral pinch maximum	Pulp pinch maximum
▪ Jamar	▪ Could not perform grip on the Jamar	▪ Pinch Gauge	▪ Pinch Gauge
▪ Dynamometer	▪ Dynamometer	▪ Dynamometer	▪ Dynamometer

3.4.2 Forces and Moments

Forces and moments were measured using a 6 degree of freedom force transducer (AMTI MC3A-6-250, Watertown, MA, USA) and amplifier (AMTI Mini Amp, MSA-6, Watertown, MA, USA). The force transducer was calibrated using the shunt calibration, and verified using known forces and moments. The signal was filtered using a 1s moving average filter. Various attachments to the force transducer were developed for each task. A moment correction (Appendix C) was developed to measure the moment applied at the grip centre of each attachment rather than the centre of the force cube. For power and volar grips, this was the 3rd metacarpal of the right hand, for pinch grips, this was a point directly between the thumb and forefinger (Grieg 2001, Edgren et al. 2004).

A program was developed (Labview 7.1, National Instruments, Austin, USA) to provide force and moment feedback to help participants apply forces and moment within +/- 10% of their target. Figure 2 is an example of someone using visual feedback to match the vertical force and radial deviator moment necessary to hold this hammer. They are attempting to maintain all other forces and moments as close to zero as possible. The visual resolution of this feedback was 0.6N for forces in the horizontal plane (Fx and Fy), 0.8N for vertical forces (Fx), 0.06Nm for moments about the horizontal axes (Mx and My) and 0.01Nm for the moment about the vertical axis (Mz).

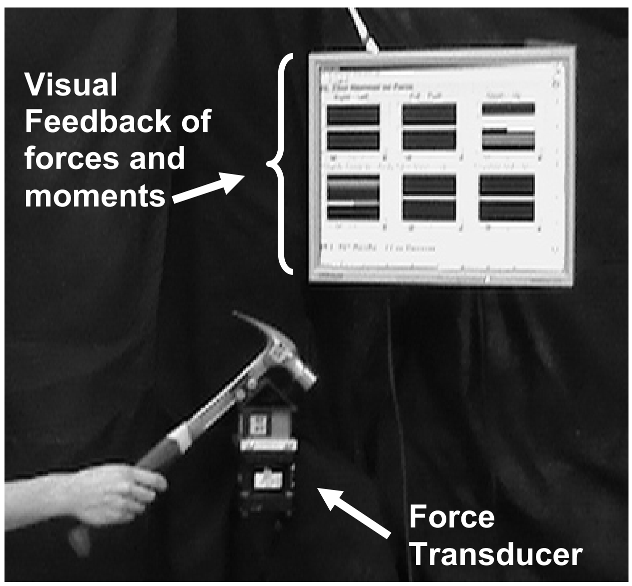


Figure 2: Participant using visual feedback to match forces and moments in 6 directions

3.4.3 Electromyography (EMG)

The activity of 8 hand and forearm muscles was used to estimate human demand (Table 7). These muscles were chosen because of their relationship to a variety of hand functions such as different grips, different directions of force application and ease of surface measurement (Greig, 2001). Surface sites were determined using the fine wire insertion points from Delagi (1975) and from Zipp (1982), when available. The skin above these locations was shaved and abraded with an alcohol water solution. Silver-silver chloride electrodes (Medicotest Blue Sensor N-00-S electrodes) were applied at an interelectrode distance of 2cm. EMG was collected with a bandwidth of 10-1000Hz (AMT-8, Bortec Biomedical Ltd., Calgary, Canada). The EMG signal was full wave rectified and filtered using a 1s moving average filter. Maximum voluntary electrical (MVE) activity was obtained by having participants apply maximal moments in 6 directions (positive and negative about 3 axes) against resistance. This was repeated 3 times and the maximum full-wave rectified value of the data filtered using a 1-second moving average was used (Mathiassen et al. 1995). If any higher activation was noted at any other time in the collection (grip maximums or tasks requiring high forces and moments), this value was used as the new maximum. Two quiet trials were collected, with participants relaxing their hand and forearm. The minimum activation from these trials after full-wave rectification and filtering was subtracted from all other signals. The maximum activation with the quiet values subtracted was used to normalize the muscle activity from all muscles as %MVE.

Table 7: Muscles Surface EMG sites

Extensor carpi ulnaris	**ECU**
Extensor carpi radialis	**ECR**
Extensor digitorum	**ED**
Flexor digitorum superficialis	**FDS**
Flexor carpi raidalis	**FCR**
Flexor carpi ulnaris	**FCU**
Flexor pollicis longus	**FPL**
First dorsal interossei	**FDI**

3.4.4 Fatigue

The testing protocol took approximately 7 hours to complete. Participants were required to rest after practicing a task before performing it once more for collection and they were allowed to rest at any other time they wanted. To determine whether fatigue was a consideration, participants performed a reference task both at the beginning and end of the protocol. The reference task consisted of applying a 30N grip force to a hand-held dynamometer in a seated posture with the forearm at 90º to the upper arm, resting on the arm rest of a chair. The mean power frequency of each muscle being monitored was calculated for both repetitions of the reference task and the percent change determined. A paired t-test ($p<0.05$) was used to compare the mean power frequency for the reference tasks at the beginning and end of the protocol.

3.4.5 Maximal moments vs. maximum grips and pinches

Maximum exertion was elicited for the purpose of normalizing EMG by having participants exert maximum moments in 6 directions. If higher activation was found through pinch and grip maximums or during tasks, this value was used as the new maximum. A comparison of the maximum activation elicited through the application of maximum moments was compared with that determined using pinch and grip maximums.

3.4.6 Posture

Hand and forearm posture was measured using electrogoniometers. This included measurement of flexion/extension, radial/ulnar deviation (twin axis goniometer, Penny & Giles Biometrics Ltd., Gwent, UK) and pronation/supination (single axis torsiometer, Penny & Giles Biometrics Ltd., Gwent, UK). For flexion/extension and radial/ulnar deviation, one end block of the goniometer was fixed with double sided tape to the centre of the back of the hand, the other end, during full flexion, to the centre of the wrist. For measuring pronation and supination, one end block of the torsiometer was fixed to the center of the underside of the wrist and the other to the ulnar side of the forearm with the torsiometer at approximately half of its full extension. The goniometers were calibrated by having participants hold a variety of positions with known posture, similar to those used by Johnson et al. (2002). Cross-talk was minimized by calibrating in the position of pronation/supination most commonly encountered (Johnson et al., 2002) using the method suggested by Buchholz and Wellman (1997). The signal was filtered using a 1 second moving average filter. Figure 3 is an example of a participant with a fully instrumented forearm including electrodes and electrogoniometers pushing on the 35mm vertical handle with force and moment feedback in 1 direction.

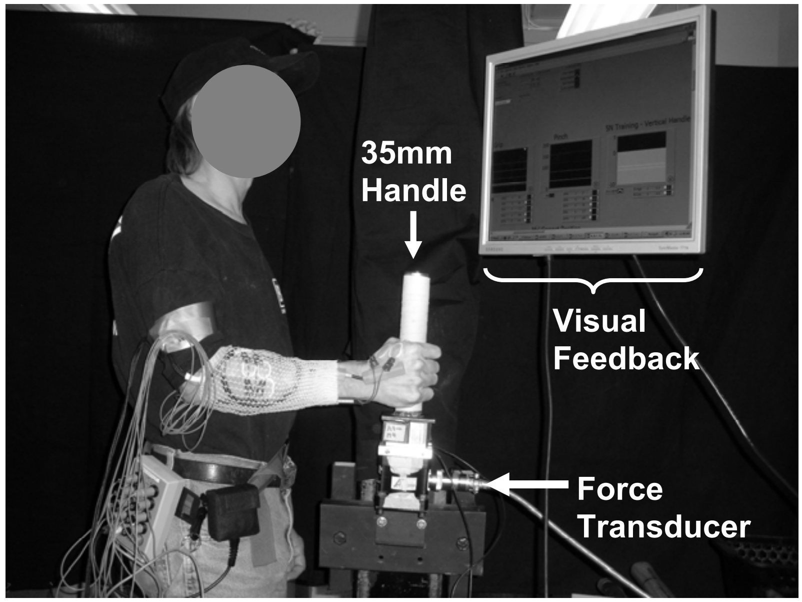


Figure 3: Example of a fully instrumented participant

3.4.7 Perceived Effort

Participants were trained to associate their perceived effort with a percentage of their maximum grip strength. To do this, participants were required to grip at a specific percentage of their maximum grip strength, and hold that force for 5 seconds. The researcher then asked the participant to associate the feeling in their hand and forearm, with the related rating of hand/wrist effort as seen on a visual analog scale. This was done at 0%MVC, increasing to 100%MVC in increments of 25%. This was repeated using a lateral pinch and the appropriate force gauge. The use of 5 benchmarks was chosen to reduce error in exertion estimation similar to Marshall, Armstrong & Ebersole (2004). After completing a task, participants rated their perceived effort on a 40mm linear potentiometer with an output from 0-100 without any markings (Figure 4).

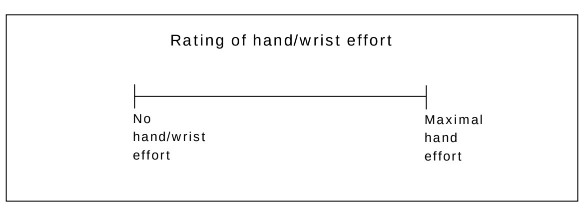


Figure 4: Perceived effort label

3.4.8 Data collection

Data was collected at 2048 Hz using NIAD Collection software (version 1.0.0.10, University of Waterloo, 2001). For each task, data was collected for 5s. For static tasks, the normalized muscle activation, and filtered posture, forces and moments were averaged over the middle 3s of each task. For dynamic tasks muscle activation, posture, forces and moments were averaged over the duration of the exertion, determined when force or muscle activation exceeded 2x the standard deviation of quiet resting before the trial began, in most cases less than 3s.

3.5 Experimental Design

The experimental design was completely randomized. The independent variable was simulation type (Simulations A, B, C, D). The dependant variables were the average percentage of maximum voluntary exertion for 8 muscles, posture, the perceived effort and the estimated grip or pinch force.

3.6 Statistical Analysis

Each manual task was considered a treatment group, including the criterion task and its simulations.

3.6.1 Comparisons within each task

For each manual task (each treatment group), all simulations were compared to the criterion task using 3 methods. The first was whether the average demand of all participants was within ±5% of the criterion task for each measured parameter described by a yes (indicating within ±5%) or a no. The range of ±5% was chosen because it is a similar size to that used by the Strain Index (Moore & Garg 1995) to differentiate between intensities of exertion.

The second method involved a comparison of the muscle activation, posture and applied force and moments for the criterion task, A, compared to each simulation, B, C, and D, using a series of two-way repeated measures ANOVAs ($\alpha = 0.05$) with type of simulation by participant where participant was a repeated measure. This was done for each task and parameter separately. Tasks and parameters were not combined because there were expected differences due to the variety of tasks used. The normality of the data was checked by looking at the linearity of a Q-Q plot of the residuals compared to the normal distribution. Sphericity was verified using Mauchley's test. The Levene test showed that the variance of the EMG data was not homogeneous for many tasks. A natural logarithmic transformation corrected this in almost all cases and ensured the assumptions of the ANOVA were met. A Dunnett post-hoc was used to determine whether the simulations were different from the criterion task, if the simulation type was a significant source of variance in the model. This method of comparing simulations does not vary depending on magnitude of forces and moments required to complete the task.

The third method of comparing simulations with the criterion task (A) with each of the simulations (B, C, D) was an intraclass correlation coefficient. ICC(3,1) was used to look at the fixed effects of the real task compared with each simulation (Bland & Altman, 1990, Shrout & Fleiss, 1979, Weir, 2005).

3.6.2 Comparisons across all tasks

To determine which simulation best matched the criterion task, each task was ranked according to the magnitude of each parameter, the EMG of each muscle, perceived effort and estimated grip force. The Spearman rank correlation was used to compare rankings between the criterion task and each simulation for all parameters.

3.6.3 Comparison with normative data

A comparison of the demand measured for each simulation was made to normative data. The maximum force and moment capabilities of the hand and forearm were found from limited sources in the literature. Greig & Wells (2004) was the primary source of average male capability chosen because the situations in which this normative data was collected were most similar to the simulations with simplified parts, standard posture and 5 second static exertion (D) used in this research. The percentage of these maximum values required for each task was determined using the mechanical demand of the task. For tasks with forces and moments applied in more than one direction, the direction, in this thesis the direction of largest relative demand was used. It was anticipated that the direction of highest normative relative demand required by a task would dominate the human demand. Wells, Greig & Ishac (2007) have reported a method to incorporate multiple measures of demand. Normative relative demand was compared to the perceived effort and grip force matching using the Pearson correlation coefficient. Based on visual inspection, this highest demand determined using normative data was most similar to that estimated using perceived effort and grip force matching supporting the strategy used.

Table 8 gives an example of the normative demand calculated for the large drill push & torque task (Task 9). The pronator moment requirement of the task creates the highest demand and this value was compared to the perceived effort and grip force matching of the criterion task and the simulations.

Table 8: Example of the normative demand required for a task

Mechanical Demand Values taken from Task 9: Large drill push and torque		**Normative Demand** Hand Capability (Greig & Wells 2004)	Relative Demand (%Max)
Upwards force (N)	23.2	194.6	12
Push force (N)	5.0	113.6	4.4
Pronator moment (Nm)	3.5	8.1	43

4 Results

The purpose of the results section is to document whether there were systematic differences between methods of simulating the criterion task. This research involved comparison of at least 3 simulations (B, C, D) of 20 manual tasks to the criterion task (A). The first part of the results contains the within task results for all 20 manual tasks The individual tasks have been organized into groups of similar activities that are presented together followed by a summary discussion. The next section contains the normative data comparison.

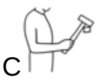
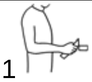
One participant could not perform the tasks adequately and was dropped from the experimental protocol giving 11 participants.

For the first task, a sledge hammer hold, the full results are shown (Table 9 to Table 11) as well as the summary Table 12. In the remaining tasks only the summary table is shown. Detailed information for all tasks can be found in Appendices D, and E.

4.1 Hammer holds (Tasks 1 - 4)

Task 1 Sledge Hammer Hold - The perceived effort, estimated grip force, muscle activation and posture for this task can be found in Table 9. The intraclass correlation coefficient comparing each simulation with the criterion task (A) can be found in Table 10. A table comparing the percentage of participants with perceived effort, grip and EMG values within ±5% of the criterion task can be found in Table 11. A graph of these results for perceived effort can be found in Figure 5. This shows that the perceived effort of the simulations is outside of the ±5% range. This graph also shows the range of perceived effort from all 11 participants based on the differing strength capabilities of 11 different men performing the same task. A similar graph for grip force matching can be seen in Figure 6 and an example of EMG for extensor digitorum activation can be found in Figure 7. A results summary, similar to that used for subsequent tasks, can be found in Table 12. This summary table shows that the best simulation is that with simplified parts and a 35mm 45º handle (D1) because it has the highest ICC values and the most average parameters within ±5% of the criterion task.

Table 9: Comparison of perceived effort, estimated grip force (Grip), muscle activation (ECU, ED, ECR, FCU, FCR, FDS, FPL, FDI), ulnar/radial deviation (Uln/Rad Dev), pronation/supination (Pro/Sup), flexion/extension (Flex/Ex) for the Sledge Hammer Hold

		A 	C 	D1 	D2 	D3 
RPE	**(%Max)**	**27.6**	**44.8**	**38.7**	**40.6**	**43.2**
Grip	**(%MVC)**	**27.7**	**33.3**	**33.0**	**35.7**	**29.8**
ECU	**(%MVE)**	**18.2**	**34.7**	**35.2**	**30.4**	**47.0**
ED	**(%MVE)**	**24.6**	**35.9**	**38.3**	**33.5**	**44.6**
ECR	**(%MVE)**	**15.4**	**26.6***	**25.7***	**27.3**	**26.5***
FCU	**(%MVE)**	**9.6**	**10.6**	**8.6**	**12.7**	**8.1**
FCR	**(%MVE)**	**7.8**	**7.7**	**8.1**	**9.5**	**11.6**
FDS	**(%MVE)**	**11.6**	**13.2**	**14.4**	**17.4**	**15.0**
FPL	**(%MVE)**	**14.3**	**26.2**	**27.7***	**31.9***	**38.3***
FDI	**(%MVE)**	**19.0**	**31.5**	**17.8**	**24.4**	**43.5***
Uln/Rad Dev	**+Uln (º)**	**15**	**15.3**	**28.4**	**22.7***	**43.0***
Pro/Sup	**+Pro (º)**	**10**	**10.1**	**18.7**	**29.5***	**-17.1**
Flex/Ex	**+Flex (º)**	**-42**	**-41.8**	**-37.8**	**-15.6**	**-7.0**
Upward force	**(N)**	**20.0**	**20.0 ± 5.4**	**19.4 ± 8.4**	**18.4 ± 8.4**	**19.2 ± 5.5**
Radial deviator moment	**(Nm)**	**5.73**	**4.63 ± 1.67**	**3.99 ± 1.44**	**4.32 ± 1.88**	**3.67 ± 1.56**

*** Indicates significant difference from the criterion task (A) p < 0.05**

Table 10: Comparison of the intraclass correlation coefficient (ICC) between the criterion task (A) for the Sledge Hammer Hold and each of the simulations for all parameters

	A-C	A-D1	A-D2	A-D3
RPE	**0.42**	**0.36**	**0.18**	**0.16**
Grip	**0.55**	**0.74**	**0.71**	**0.34**
ECU	**0.71**	**0.72**	**0.68**	**0.47**
ED	**0.69**	**0.36**	**0.47**	**0.65**
ECR	**0.67**	**0.64**	**0.46**	**0.61**
FCU	**0.19**	**0.39**	**0.27**	**0.37**
FCR	**0.55**	**0.90**	**0.41**	**0.01**
FDS	**0.66**	**0.62**	**0.36**	**0.55**
FPL	**0.64**	**0.61**	**0.30**	**0.21**
FDI	**0.54**	**0.71**	**0.49**	**0.40**
Average EMG	**0.58**	**0.62**	**0.43**	**0.41**

The ICC was calculated for the average of all participants using a two-way fixed effects ANOVA for each simulation compared to the criterion task

Table 11: Comparison of whether the average of all participants was within ±5% of the criterion for the Sledge Hammer Hold (indicated by Y=yes or N=no) and the percentage of participants within +/-5% of the criterion task (A) for all measured variables and all simulations

A 	C 		D1 		D2 		D3 	
Perceived Effort	N	36%	N	27%	N	36%	N	18%
Grip	N	27%	N	27%	N	9%	Y	27%
ECU	N	36%	N	9%	N	18%	N	9%
ED	N	27%	N	0%	N	9%	N	18%
ECR	N	27%	N	27%	N	27%	N	27%
FCU	Y	73%	Y	73%	Y	64%	Y	73%
FCR	Y	82%	Y	100%	Y	73%	Y	64%
FDS	Y	64%	Y	55%	N	55%	Y	64%
FPL	N	18%	N	18%	N	9%	N	18%
FDI	N	9%	Y	36%	N	27%	N	9%
Average EMG		42%		40%		35%		35%

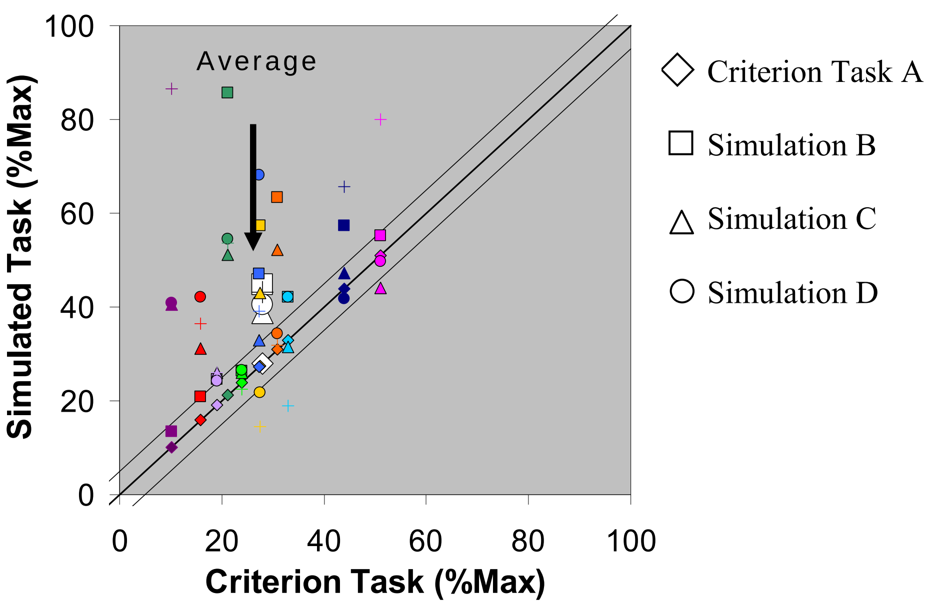


Figure 5: A plot of the perceived effort of the criterion task and the simulations for the average of all 11 participants and each individual

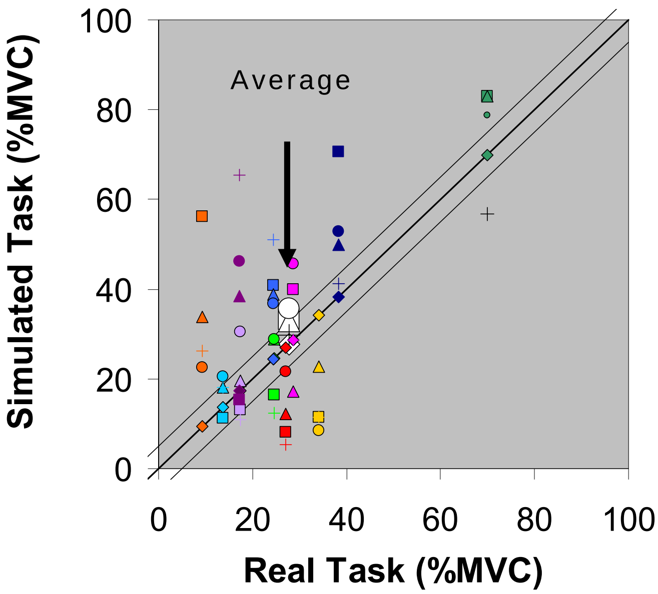


Figure 6: A plot of grip force matching of the criterion task and the simulations for the average of all 11 participants and each individual

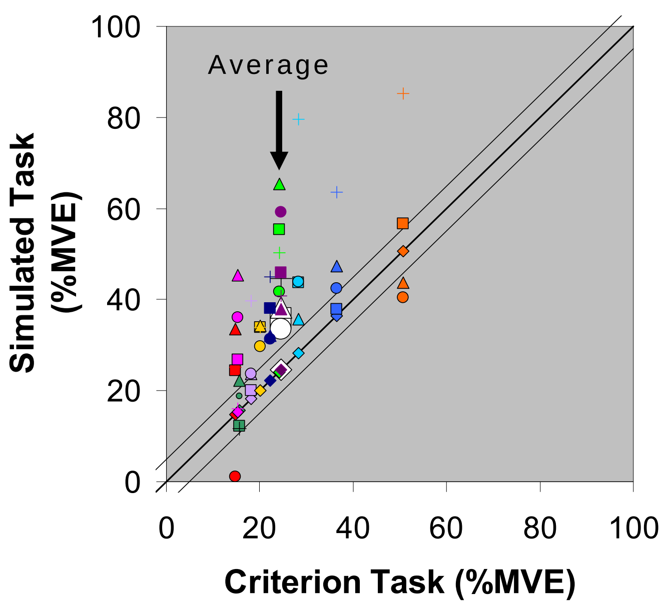


Figure 7: A plot of the extensor digitorum activation forf the criterion task and the simulations for the average of all 11 participants and each individual

Table 12: Summary of differences between the criterion task and each simulation for Task 1: Sledge Hammer Hold

	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
A 			
C 	EMG: ↑ **(7/8 not different)** Posture: **Ulnar dev.↑**	Perceived effort: **0.42** Grip: **0.55** EMG Average: **0.58**	Perceived effort: **N ↑** Grip: **N ↑** EMG: **N ↑ (3/8 within)**
D1 	EMG: ↑ **(6/8 not different)** Posture: **Ulnar dev.↑**	Perceived effort: **0.36** Grip: **0.74** EMG Average: **0.62**	Perceived effort: **N ↑** Grip: **N ↑** EMG: **Y (4/8 within)**
D2 	EMG: ↑ **(7/8 not different)** Posture: **Ulnar dev.↑**	Perceived effort: **0.18** Grip: **0.71** EMG Average: **0.43**	Perceived effort: **N ↑** Grip: **N ↑** EMG: **N ↑ (2/8 within)**
D3 	EMG: ↑ **(5/8 not different)** Posture: **Ulnar dev.↑, pronation↑**	Perceived effort: **0.16** Grip: **0.34** EMG Average: **0.41**	Perceived effort: **N ↑** Grip: **Y** EMG: **N ↑ (3/8 within)**

Task 2 22oz Hammer Hold - Table 13 shows that based on the analysis of variance, the simulations all had higher EMG than the criterion task. The best simulation was that with a simplified 35mm horizontal handle and force and moment feedback (D2). This simulation had the highest ICC values and the most average demand measures within ±5% of the criterion task.

Table 13: Summary of differences between the criterion task and each simulation of the 22oz Hammer Hold

	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
A 			
C 	Grip: ↑ EMG: ↑ **(4/8 not different)** Upward force: ↑	Perceived effort: **0.67** Grip: **0.65** EMG Average: **0.58**	Perceived effort: **N ↑** Grip: **Y** EMG: **Y (5/8 within)**
D1 	EMG: ↑ **(6/8 not different)**	Perceived effort: **0.86** Grip: **0.37** EMG Average: **0.39**	Perceived effort: **N ↑** Grip: **N ↑** EMG: **Y (4/8 within)**
D2 	EMG: ↑ **(6/8 not different)** Posture: **Ulnar dev.↑**	Perceived effort: **0.87** Grip: **0.85** EMG Average: **0.56**	Perceived effort: **Y** Grip: **Y** EMG: **Y (7/8 within)**
D3 	EMG: ↑ **(4/8 not different)** Upward force: ↑ Posture: **Ulnar dev.↓, pronation↑**	Perceived effort: **0.41** Grip: **0.27** EMG Average: **0.43**	Perceived effort: **N ↑** Grip: **N ↑** EMG: **Y (4/8 within)**

Task 3 16oz Hammer Hold: Table 14 shows that the best simulation is that with real parts and force and moment feedback (C) based on ICC and the number of parameters within ±5% of the criterion task. No significant differences in muscle activation though the upward force applied for the simulations was greater than that of the criterion task.

Table 14: Summary of differences between the criterion task and each simulation of the 16oz Hammer Hold

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
C 	EMG: **(8/8 not different)** Upward force: ↑ Rad. dev. moment: ↑	Perceived effort: **0.88** Grip: **0.95** EMG Average: **0.52**	Perceived effort: **N** ↑ Grip: **Y** EMG: **Y (8/8 within)**
D1 	EMG: **(8/8 not different)** Upward force: ↑	Perceived effort: **0.66** Grip: **0.77** EMG Average: **0.42**	Perceived effort: **N** ↑ Grip: **Y** EMG: **Y (7/8 within)**
D2 	EMG: **(8/8 not different)** Upward force: ↑ Ulnar deviation: ↑ Extension: ↑	Perceived effort: **0.81** Grip: **0.68** EMG Average: **0.46**	Perceived effort: **N** ↑ Grip: **N** ↑ EMG: **Y (7/8 within)**
D3 	EMG: ↑ **(6/8 not different)** Upward force: ↑ Rad. dev. moment: ↓ Ulnar deviation: ↓ Extension: ↑	Perceived effort: **0.47** Grip: **0.77** EMG Average: **0.27**	Perceived effort: **N** ↑ Grip: **N** ↑ EMG: **Y (7/8 within)**

Task 4 Modified Heavy Hammer Hold: Table 15 shows that based on the analysis of variance, the simulations had lower EMG than the criterion task. The upward force and radial deviator moment could not be met by most participants, a reason for lower muscle activation. The top two simulations were those with the simplified 35mm horizontal handle (D2) followed closely by the simplified 45º handle (D1). If participants had been able to meet the required upward force, there likely would have been fewer differences in the estimated demand between the simulations and the criterion task.

Table 15: Summary of differences between the criterion task and each simulation of the Modified Heavy Hammer Hold

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
C 	EMG: ↓ **(5/8 not different)** Upward force: ↓ Rad. dev. moment: ↓	Perceived effort: **0.40** Grip: **0.85** EMG Average: **0.15**	Perceived effort: **N** ↓ Grip: **N** ↓ EMG: **N (2/8 within)**
D1 	EMG: ↓ **(4/8 not different)** Upward force: ↓ Rad. dev. moment: ↓	Perceived effort: **0.87** Grip: **0.32** EMG Average: **0.34**	Perceived effort: **Y** Grip: **N** ↓ EMG: **N (1/8 within)**
D2 	EMG: ↓ **(4/8 not different)** Upward force: ↓ Rad. dev. moment: ↓ Ulnar deviation: ↑	Perceived effort: **0.90** Grip: **0.58** EMG Average: **0.21**	Perceived effort: **Y** Grip: **Y** EMG: **N (2/8 within)**
D3 	EMG: ↓ **(5/8 not different)** Upward force: ↓ Rad. dev. moment: ↓ Ulnar deviation: ↓ Extension: ↑	Perceived effort: **0.10** Grip: **-0.06** EMG Average: **0.14**	Perceived effort: **N** ↓ Grip: **Y** EMG: **N (0/8 within)**

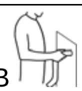
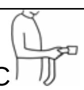
Hammer task summary

Across all hammer tasks, no simulation stood out as being the best. Difficulty meeting the high force requirements of the modified heavy hammer task (Task 4) and the low force required for the 16oz hammer (Task 3) indicate that in some cases the simulations had a different mechanical demand compared to the criterion task. This makes discussion of differences between the criterion task and its simulations difficult.

4.2 Hose insertions (Tasks 5 & 18)

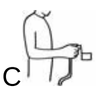
Task 5 Radiator Hose Insertion: Table 16 shows that based on the analysis of variance, the simulations all had lower EMG than the criterion task. The top two simulations were those with real parts and force and moment feedback (C) followed by that with real parts and simple feedback (B).

Table 16: Summary of differences between the criterion task and each simulation of the Radiator Hose Insertion

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: ↓ **(1/8 not different)**	Perceived effort: **0.71** Grip: **0.60** EMG Average: **0.23**	Perceived effort: **Y** Grip: **Y** EMG: **Y (5/8 within)**
C 	EMG: ↓ **(4/8 not different)** Ulnar deviation: ↑	Perceived effort: **0.80** Grip: **0.63** EMG Average: **0.14**	Perceived effort: **Y** Grip: **Y** EMG: **Y (5/8 within)**
D2 	EMG: ↓ **(6/8 not different)** Push force: ↑ Ulnar deviation: ↑ Extension: ↓	Perceived effort: **0.55** Grip: **0.70** EMG Average: **0.31**	Perceived effort: **N** Grip: **Y** EMG: **Y (6/8 within)**
D3 	EMG: ↓ **(0/8 not different)**	Perceived effort: **0.14** Grip: **0.78** EMG Average: **0.28**	Perceived effort: **N** Grip: **Y** EMG: **Y (5/8 within)**

Task 18 Power Steering Hose Insertion: Table 16 shows that all of the simulations had lower EMG than the criterion task. None of the simulations stands out as the best, though the simulation with real parts and force and moment feedback (C) is the most similar.

Table 17: Summary of differences between the criterion task and each simulation of the Power Steering Hose Insertion

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	Perceived effort: ↓ EMG: ↓ **(1/8 not different)** Extension: ↑	Perceived effort: **0.64** Grip: **0.66** EMG Average: **0.17**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (0/8 within)**
C 	EMG: ↓ **(3/8 not different)** Push force: ↑ Extension: ↑	Perceived effort: **0.73** Grip: **0.87** EMG Average: **0.13**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (1/8 within)**
D 	Perceived effort: ↓ EMG: ↓ **(1/8 not different)** Push force: ↑ Extension: ↓	Perceived effort: **0.78** Grip: **0.76** EMG Average: **0.09**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (0/8 within)**

Hose Insertion Summary

The realistic mock-ups of these tasks were dynamic, with higher EMG than the simulations. This could be due to changes in posture, degrees of freedom and force application during the task. The use of the average force for the simulations compared to the dynamic force for the criterion task is another source of this difference.

4.3 Window Seal Insertion

Task 6 Window Seal Insertion using "Pizza Wheel": Table 18 shows that the simulations of this task had zero measured parameters within ±5% of the criterion task and low ICC values. The criterion task had higher muscle activation and the average parameters were below the ±5% range specifying a good simulation. Similar to the hose insertion tasks mentioned previously, the higher muscle activation is likely due to the dynamic nature of the criterion task simulated with static tasks based on an average applied force.

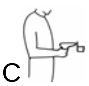
Table 18: Summary of differences between the criterion task and each simulation of the Window Seal Insertion

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: ↓ **(4/8 not different)**	Perceived effort: **0.36** Grip: **0.45** EMG Average: **0.08**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (0/8 within)**
C 	EMG: **(0/8 not different)**	Perceived effort: **0.58** Grip: **0.79** EMG Average: **0.13**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (0/8 within)**
D 	EMG: ↓ **(3/8 not different)**	Perceived effort: **0.33** Grip: **0.74** EMG Average: **0.06**	Perceived effort: **N↓** Grip: **N↓** EMG: **N↓ (0/8 within)**

4.4 Drill Tasks (Tasks 7-12)

Task 7 Large Drill Hold: Table 19 shows that the best simulations are those with real (C) or simplified parts (D) with force and moment feedback. These have the highest ICC values.

Table 19: Summary of differences between the criterion task and each simulation of the Large Drill Hold

A 	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.49** Grip: **0.82** EMG Average: **0.44**	Perceived effort: **N↑** Grip: **N↓** EMG: **Y (8/8 within)**
C 	EMG: **(8/8 not different)**	Perceived effort: **0.80** Grip: **0.62** EMG Average: **0.31**	Perceived effort: **Y** Grip: **Y** EMG: **Y (7/8 within)**
D 	EMG: **(8/8 not different)**	Perceived effort: **0.76** Grip: **0.81** EMG Average: **0.43**	Perceived effort: **Y** Grip: **Y** EMG: **Y (7/8 within)**

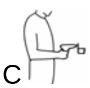
Task 8 Large Drill Push: Table 20 shows that the best simulation is that with real parts and simple feedback (B) because it has the most parameters within ±5% of the criterion task.

Table 20: Summary of differences between the criterion task and each simulation of the Large Drill Push

A 	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.32** Grip: **0.71** EMG Average: **0.79**	Perceived effort: **N↓** Grip: **Y** EMG: **Y (8/8 within)**
C 	EMG: ↓ **(5/8 not different)**	Perceived effort: **0.48** Grip: **0.74** EMG Average: **0.40**	Perceived effort: **Y** Grip: **N↑** EMG: **Y (5/8 within)**
D 	EMG: ↓ **(5/8 not different)**	Perceived effort: **0.61** Grip: **0.81** EMG Average: **0.59**	Perceived effort: **N↓** Grip: **Y** EMG: **Y (6/8 within)**

Task 9 Large Drill Push & Torque: Table 21 shows that the best simulation is that with real parts and simple feedback (B) because it has the highest ICC values and the most parameters within ±5% of the criterion task.

Table 21: Summary of differences between the criterion task and each simulation of the Large Drill Push & Torque

 A	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
 B	EMG: **(8/8 not different)**	Perceived effort: **0.58** Grip: **0.78** EMG Average: **0.44**	Perceived effort: **Y** Grip: **Y** EMG: **Y (8/8 within)**
 C	EMG: ↑ **(7/8 not different)** Ulnar Deviation: ↑	Perceived effort: **0.35** Grip: **0.14** EMG Average: **0.13**	Perceived effort: **N↑** Grip: **Y** EMG: **N↑ (2/8 within)**
 D	EMG: **(8/8 not different)** Ulnar Deviation: ↑	Perceived effort: **0.49** Grip: **0.61** EMG Average: **0.36**	Perceived effort: **N↑** Grip: **N↓** EMG: **N↑ (2/8 within)**

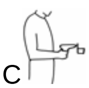
Task 10 Small Drill Hold: Table 22 shows that the best simulation is difficult to pick out, all simulations represented the demand required for the criterion task well. The simulation with the highest ICC values is that with real parts and simple feedback (B).

Table 22: Summary of differences between the criterion task and each simulation of the Small Drill Hold

 A	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
 B	EMG: **(8/8 not different)**	Perceived effort: **0.76** Grip: **0.74** EMG Average: **0.64**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (8/8 within)**
 C	EMG: **(8/8 not different)** Upward force: ↑	Perceived effort: **0.17** Grip: **0.55** EMG Average: **0.18**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (7/8 within)**
 D	EMG: **(8/8 not different)**	Perceived effort: **0.72** Grip: **0.42** EMG Average: **0.36**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (8/8 within)**

Task 11 Small Drill Push: Table 23 shows that the best simulation is again difficult to pick out. The simulation with the highest ICC values is that with a 35mm vertical handle (D) though it had significantly lower grip force estimation.

Table 23: Summary of differences between the criterion task and each simulation of the Small Drill Push

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.50** Grip: **0.75** EMG Average: **0.67**	Perceived effort: **N↓** Grip: **N↓** EMG: **Y (8/8 within)**
C 	Perceived effort: ↓ Grip: ↓ EMG: **(8/8 not different)**	Perceived effort: **0.71** Grip: **0.46** EMG Average: **0.61**	Perceived effort: **N↓** Grip: **N↓** EMG: **Y (7/8 within)**
D 	Grip: ↓ EMG: **(8/8 not different)**	Perceived effort: **0.70** Grip: **0.82** EMG Average: **0.53**	Perceived effort: **N↓** Grip: **N↓** EMG: **Y (8/8 within)**

Task 12 Small Drill Push & Torque: Table 24 shows that the best simulation was that with real parts and simple feedback (B). This simulation had the most similar muscle activation and the highest ICC values.

Table 24: Summary of differences between the criterion task and each simulation of the Small Drill Push & Torque

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.59** Grip: **0.78** EMG Average: **0.61**	Perceived effort: **N↑** Grip: **N↓** EMG: **Y (8/8 within)**
C 	EMG: ↑ **(5/8 not different)** Pronation: ↑	Perceived effort: **0.38** Grip: **0.78** EMG Average: **0.40**	Perceived effort: **N↑** Grip: **N↓** EMG: **N↑ (3/8 within)**
D 	EMG: ↑ **(5/8 not different)** Push force: ↑ Ulnar deviation: ↑	Perceived effort: **0.70** Grip: **0.87** EMG Average: **0.32**	Perceived effort: **Y** Grip: **N↓** EMG: **N↑ (3/8 within)**

Drill Task Summary

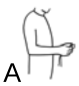
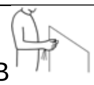
Drill simulations with real parts and simple feedback (B) estimated a demand most similar to the criterion task. A simple drill hold for both the large (Task 7) and small (Task 10) drills had the fewest differences from the criterion task. Adding a push force and torque (a pronator moment) increased the estimated demand between the criterion task (A) and the simulations. Adding more non-zero forces and moments could have increased the mental demand of the task making it more difficult to hit targets (MacDonell & Keir 2003).

The grip force matching values for drill tasks without torque were lower than those of drill forces tasks with torque. For example, the large drill hold had an average grip force matching value of 21%MVC whereas the large drill push and torque had an average grip force matching value of 34%MVC. Similar to findings by Lin et al. (2009), the application of torque resulted in higher estimated grip force determined through grip force matching.

4.5 Wire harness connectors

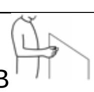
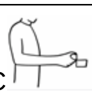
Task 13 Wire Harness Connector ORC1 (wires): Table 25 shows that the best simulation was that with a simplified vertical 35mm handle (D) with force and moment feedback. This simulation had the highest ICC values and the most measures of demand within ±5% of the criterion task.

Table 25: Summary of differences between the criterion task and each simulation of the Wire Harness Connector ORC1 (wires)

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	Grip: ↓ EMG: ↓ **(3/8 not different)**	Perceived effort: **0.24** Grip: **0.62** EMG Average: **0.23**	Perceived effort: **Y** Grip: **N↓** EMG: **N↓ (1/8 within)**
C 	Grip: ↓ EMG: **(8/8 not different)** Push Force: ↓	Perceived effort: **0.26** Grip: **0.06** EMG Average: **0.40**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (6/8 within)**
D 	EMG: **(8/8 not different)** Push Force: ↓ Ulnar deviation: ↓	Perceived effort: **0.37** Grip: **0.35** EMG Average: **0.39**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (6/8 within)**

Task 14 Wire Harness Connector ORC2 (no wires): Table 26 shows that the best simulation was that with real parts and force and moment feedback (C) followed closely by the simulation with simplified parts and force and moment feedback (D). These simulations had the highest ICC values and the most parameters within ±5% of the criterion task.

Table 26: Summary of differences between the criterion task and each simulation of the Wire Harness Connector ORC2 (no wires)

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	Grip: ↓ EMG: ↓ **(3/8 not different)**	Perceived effort: **0.50** Grip: **0.24** EMG Average: **0.25**	Perceived effort: **Y** Grip: **N↓** EMG: **N↓ (2/8 within)**
C 	Grip: ↓ EMG: **(8/8 not different)**	Perceived effort: **0.81** Grip: **0.80** EMG Average: **0.30**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (6/8 within)**
D 	EMG: **(8/8 not different)** Ulnar deviation: ↓	Perceived effort: **0.69** Grip: **0.74** EMG Average: **0.24**	Perceived effort: **Y** Grip: **N↓** EMG: **Y (6/8 within)**

Wire Harness Connector Summary

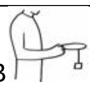
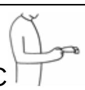
The best simulations were those with force and moment feedback (C and D) for both wire harness connectors. Grip force matching of the simulations tended to underestimate the grip force matching of the criterion task.

The criterion task was a dynamic connection that required participants to push until the connector clicked into place. Simulations with static posture, lower degrees of freedom and average applied force all contribute to the underestimation of the required pinch force.

4.6 Plate holds

Task 15 0.5kg Plate Hold: Table 27 shows that the best simulation was that with real parts and simple feedback (B). This simulation had the highest ICC values and the most indicators of demand within ±5% of the criterion task.

Table 27: Summary of differences between the criterion task and each simulation of the 0.5kg Plate Hold

A 	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.85** Grip: **0.77** EMG Average: **0.54**	Perceived effort: **Y** Grip: **N↑** EMG: **Y (8/8 within)**
C 	EMG: **(8/8 not different)**	Perceived effort: **0.62** Grip: **0.61** EMG Average: **0.71**	Perceived effort: **Y** Grip: **N↑** EMG: **Y (7/8 within)**
D 	EMG: ↑ **(6/8 not different)** Ulnar deviation: ↓	Perceived effort: **0.40** Grip: **0.06** EMG Average: **0.35**	Perceived effort: **N↑** Grip: **N↑** EMG: **Y (5/8 within)**

Task 16 2.2kg Plate Hold: Table 28 shows that the best simulation is difficult to pick out. The simulation with real parts and simple feedback (B) is similar to that of real parts and force and moment feedback (C) based on ICC values and the number of parameters within ±5% of the criterion task.

Table 28: Summary of differences between the criterion task and each simulation of the 2.2kg Plate Hold

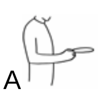
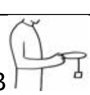
A 	Significant differences from A	Average ICC Compared with A	Average within ±5% of A? Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)**	Perceived effort: **0.55** Grip: **0.07** EMG Average: **0.20**	Perceived effort: **N↓** Grip: **Y** EMG: **Y (6/8 within)**
C 	EMG: **(8/8 not different)**	Perceived effort: **0.61** Grip: **0.54** EMG Average: **0.50**	Perceived effort: **N↓** Grip: **N↓** EMG: **Y (6/8 within)**
D 	EMG: ↑ **(6/8 not different)**	Perceived effort: **0.32** Grip: **-0.33** EMG Average: **0.38**	Perceived effort: **N↑** Grip: **Y** EMG: **N↑ (3/8 within)**

Plate Hold Summary

For both plate holds the best simulations were those with real parts. The simulation with simplified parts had a significantly thicker handle being pinched (25mm compared with 3mm plate). Increasing handle thickness from 10mm to 50mm was shown to increase maximum pinch for males from 55N to 66N by Depmsey & Ayoub (1996).

4.7 Fastener initiations

Task 17 Fastener Initiation Extended Posture: Table 29 shows that the best simulation is difficult to pick out. Those simulations with few significant differences do not correspond to those with high ICC values or the parameters within ±5% of the criterion task.

Table 29: Summary of differences between the criterion task and each simulation of the Fastener Initiation Extended Posture

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: ↓ **(1/8 not different)**	Perceived effort: **0.28** Grip: **0.11** EMG Average: **0.36**	Perceived effort: **Y** Grip: **N↑** EMG: **Y (7/8 within)**
C 	EMG: ↓ **(6/8 not different)**	Perceived effort: **0.17** Grip: **0.22** EMG Average: **0.39**	Perceived effort: **N↑** Grip: **N↑** EMG: **Y (6/8 within)**
D 	EMG: ↓ **(4/8 not different)**	Perceived effort: **0.64** Grip: **-0.09** EMG Average: **0.47**	Perceived effort: **Y** Grip: **N↑** EMG: **Y (8/8 within)**

Task 19 Fastener Initiation Neutral Posture: Table 30 shows again, that the best simulation is difficult to pick out. Those simulations with few significant differences do not correspond to those with high ICC values or the parameters within ±5% of the criterion task.

Table 30: Summary of differences between the criterion task and each simulation of the Fastener Initiation Neutral Posture

 A	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
 B	EMG: ↓ **(6/8 not different)** Ulnar Deviation: ↑	Perceived effort: **0.31** Grip: **0.18** EMG Average: **0.35**	Perceived effort: **N** Grip: **N** EMG: **Y (7/8 within)**
 C	EMG: ↓ **(4/8 not different)**	Perceived effort: **0.64** Grip: **0.36** EMG Average: **0.19**	Perceived effort: **Y** Grip: **Y** EMG: **Y (5/8 within)**
 D5	EMG: ↓ **(4/8 not different)**	Perceived effort: **0.43** Grip: **-0.06** EMG Average: **0.54**	Perceived effort: **Y** Grip: **Y** EMG: **Y (7/8 within)**
 D6	EMG: **(8/8 not different)**	Perceived effort: **0.18** Grip: **0.51** EMG Average: **0.38**	Perceived effort: **N** Grip: **Y** EMG: **Y (7/8 within)**

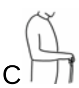
Fastener Initiation Summary

These dynamic task were simulated with static tasks based on the average applied forces and moments. The forces and moments were at the end range of the resolution of the system, making it difficult for participants to hold the required force and moment, resulting in variation that may be masking any trends.

4.8 Brakeline Cap

Task 20 Brakeline Cap Pull: Table 31 shows that the best simulation was that with real parts and simple feedback (B). This simulation had the most similar muscle activation and the most parameters within ±5% of the criterion task. Most simulations had lower EMG than the criterion task. Because the simulations were based on the average pull force required for criterion task, they may be underestimating the demand required.

Table 31: Summary of differences between the criterion task and each simulation of the Brakeline Cap

A 	**Significant differences from A**	**Average ICC Compared with A**	**Average within ±5% of A?** Y indicates parameter is within ±5% (with % of EMG), N indicates it is not with direction of difference
B 	EMG: **(8/8 not different)** Upward force: ↑	Perceived effort: **0.32** Grip: **0.76** EMG Average: **0.50**	Perceived effort: **Y** Grip: **Y** EMG: **Y (7/8 within)**
C 	EMG: ↓ **(7/8 not different)**	Perceived effort: **-0.08** Grip: **0.81** EMG Average: **0.45**	Perceived effort: **Y** Grip: **N ↓** EMG: **Y (6/8 within)**
D7 	EMG: ↓ **(5/8 not different)** Posture: **Ulnar dev.↑, Extension ↑**	Perceived effort: **-0.20** Grip: **0.61** EMG Average: **0.14**	Perceived effort: **Y** Grip: **Y** EMG: **Y (5/8 within)**
D3 	EMG: ↓ **(6/8 not different)** Upward force: ↑ Posture: **Flexion ↑**	Perceived effort: **-0.12** Grip: **0.63** EMG Average: **0.14**	Perceived effort: **N** Grip: **N ↓** EMG: **N (3/8 within)**

4.9 Summary

The three methods of analysis used, ANOVA to determine differences from the criterion task, whether the average was within ±5% of the criterion task (Table 32) and an ICC comparing the simulations to the criterion task, were compared to determine which simulation best estimated demand. Details can be found in Appendix F. Overall, simulation B with real parts and simple feedback had a demand most similar to the criterion task, followed by simulation C with real parts and force and moment feedback. The simulation with demand least similar to the criterion task was simulation D with simplified parts and force and moment feedback.

Table 32: Comparison of the percentage of perceived effort, grip force matching and EMG within ±5% and ±10% of the criterion task for each simulation

	Range of criterion task (A)	Percentage of values within specified range		
		Simulation B	Simulation C	Simulation D
Perceived Effort	Within ±5%	50	45	30
	Within ±10%	88	85	75
Grip force matching	Within ±5%	31	30	35
	Within ±10%	69	65	70
EMG	Within ±5%	75	70	60
	Within ±10%	88	85	85

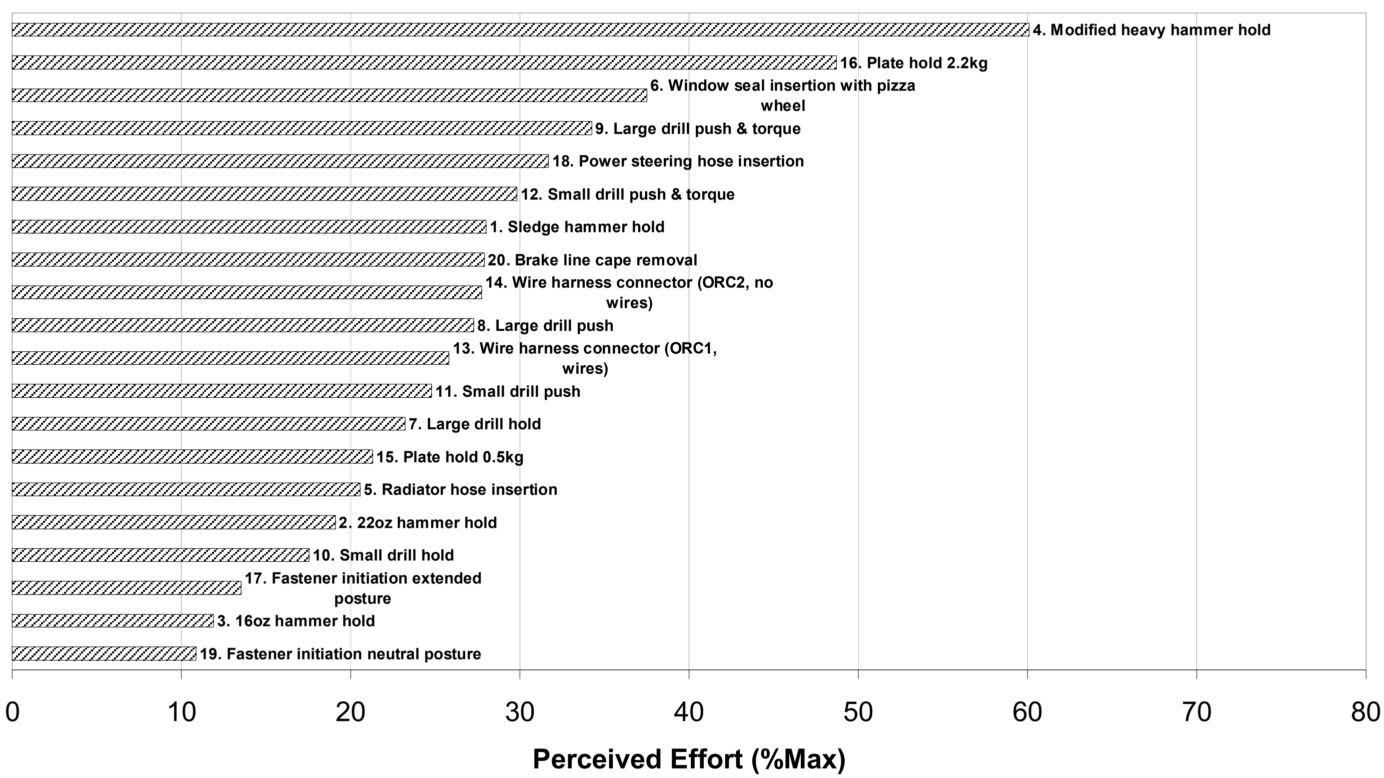


Figure 8: Average perceived effort for all participants and all tasks in rank order of magnitude

4.10 Simulation-Based Results

Combining all tasks, the simulation that represented the criterion task with the fewest differences, was determined by ranking the response magnitude for perceived effort, grip force matching and EMG (Appendix G). As an example, Figure 9 shows the average perceived effort for all tasks ranked in order of magnitude. The rankings were correlated using Spearman's rank correlation. Figure 10 shows that the highest rank correlation based on perceived effort and grip force matching was that of simulation B with real parts and simple feedback. The highest rank correlation averaged across all 8 muscles of EMG was simulation C with real parts and force and moment feedback in 6 directions. Simulation D had the lowest rank correlation for perceived effort, grip force matching and average EMG.

Averaging the rank correlation across all simulations (Figure 11) shows that perceived effort and grip force matching had similar rank correlations with the criterion task while the average EMG was lower. Of all the muscles studied, extensor digitorum had the highest rank correlation with the criterion task (0.68) followed by flexor carpi ulnaris, flexor carpi radialis and the first dorsal interosseus (all at 0.64).

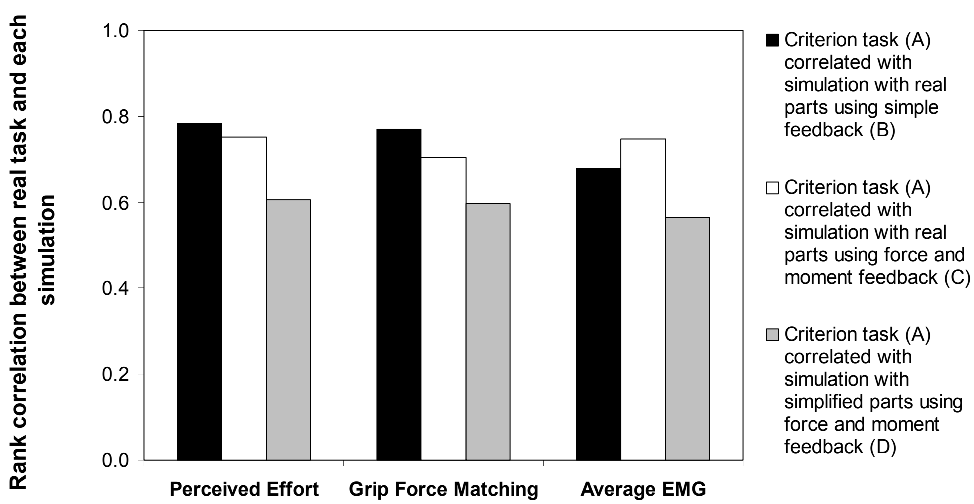


Figure 10: Comparison of the correlation between the rankings of each simulation with the real task for all measured parameters

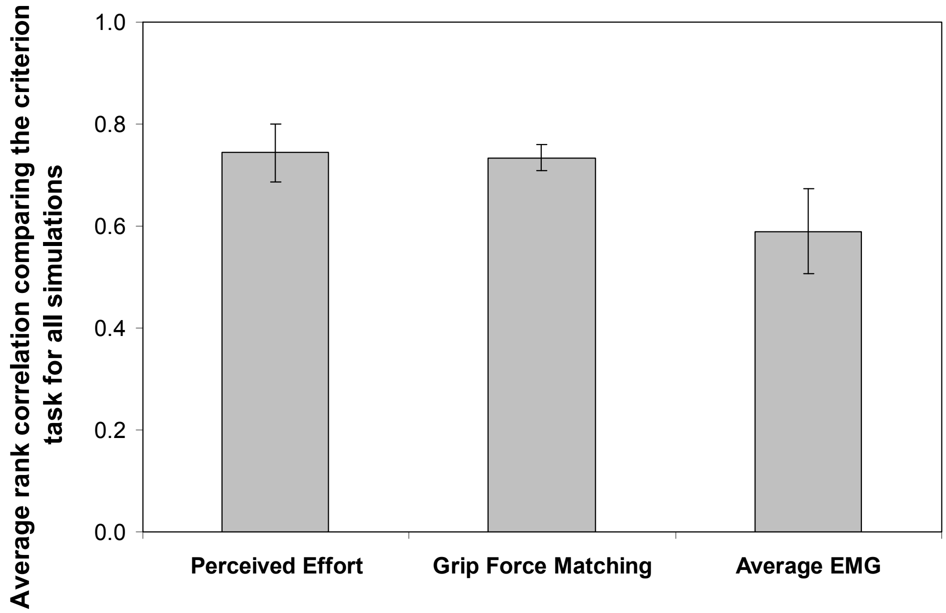


Figure 11: Comparison of the average rank correlation for all simulations with the criterion task for perceived effort, grip force matching and average EMG

4.11 Comparison with normative data

Appendix H shows the relative normative demand of the average male determined by the forces and moments required for each task and normative data. For tasks with multiple forces and moments, the highest relative demand was used for comparison with the task simulations and is shown in bold.

Figure 12 is a plot of the perceived effort compared with normative demand for the criterion task (A). The correlation between the normative relative data demand and perceived effort was 0.56. It can be seen from this graph that the perceived effort of 17 tasks is greater than the demand determined using normative data. Figure 13 is a plot of the demand determined using grip force matching compared with normative data for the criterion task (A). The correlation between the normative relative demand and grip force estimation was 0.18. Again the demand determined using grip force matching appears greater than that determined using normative data for 15 tasks.

Table 33 gives the correlation coefficients for the most realistic version of all tasks compared with the physical demand determined using normative data. It can be seen from this table that the criterion task (A) and the simulation with real parts and simple feedback (B) have the lowest correlation while the simulations with real parts (C) and simplified parts (D) and force and moment feedback have a higher correlation with the demand determined using normative data. This is expected because these simulations share many characteristics with the normative data, for example the method of feedback, forces and moments in 6 directions.

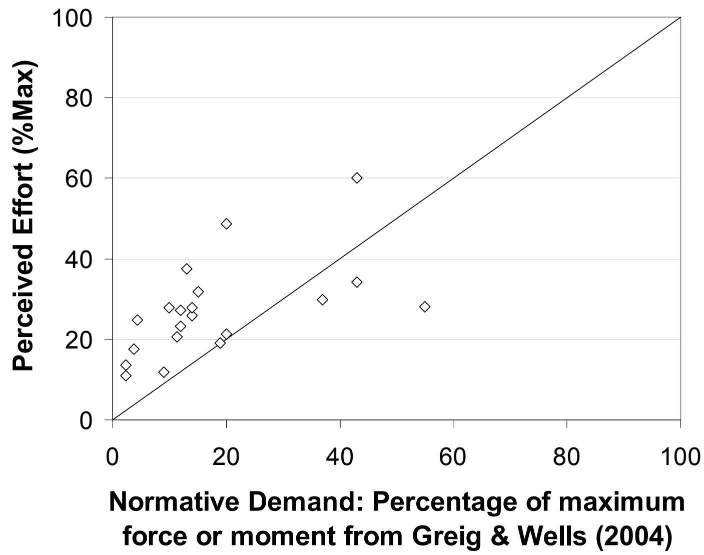


Figure 12: Comparison of relative demand determined using normative data with that determined using the perceived effort for the criterion task, simulation A

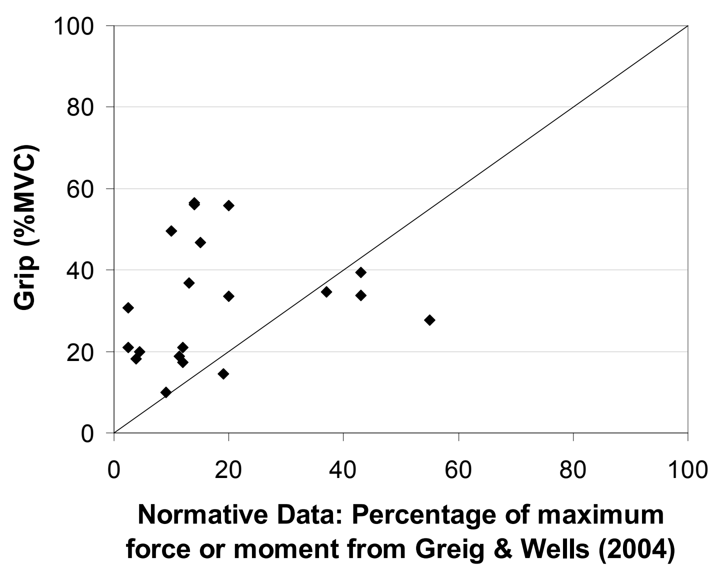


Figure 13: Comparison of relative demand determined using normative data with that determined using estimated grip force determined using grip force matching for the criterion task, simulation A

Table 33: Correlation of demand estimated using perceived effort and grip force matching with that determined using limited normative data from the literature and mechanical demand

Correlation with normative data	Perceived Effort	Grip Force Matching
Simulation A: Criterion task Most realistic with real parts, posture and timing	**0.56**	**0.18**
Simulation B: Real parts with simple feedback, standard postures and 5s timing	**0.56**	**0.14**
Simulation C: Real parts with force and moment feedback, standard postures and 5s timing	**0.90**	**0.28**
Simulation D: Simplified parts designed to mimic normative data collection methods with force and moment feedback, standard postures and 5s timing	**0.80**	**0.29**

The demand determined using normative data was based on the application of a force or moment in one direction and was lower, in most cases, than that determined using perceived effort. Perceived effort considers more than just a single direction of force or moment application and may account for the loading in multiple structures, perhaps the highest loading of all involved structures. The demand determined using grip force matching did not correlate well with the relative normative demand.

4.12 Maximal moments vs. maximum grips and pinches

In this research, the maximum muscle activation elicited using maximum moments was used to normalize participants' EMG. This activation was compared to that measured using maximum pinches and grips. For most participants, higher activation was elicited by the exertion of maximum moments than by grip or pinch maximums. Figure 14 shows the average maximum exertion for all participants as determined by maximum moments compared with pinch and grip maximums.

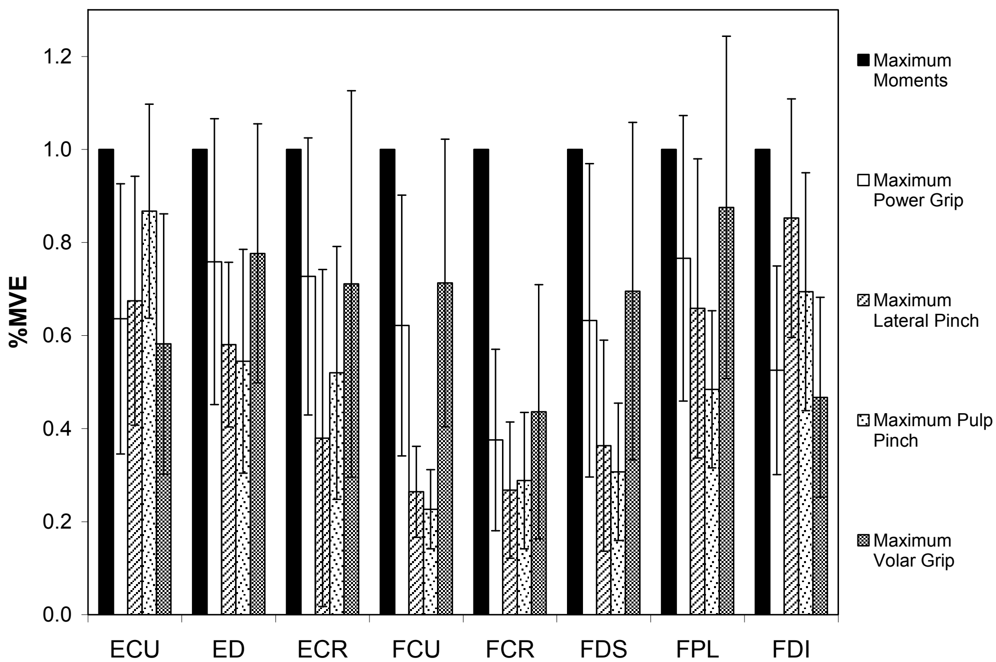


Figure 14: Comparison of average maximum muscle activation elicited using maximum moments compared with that of grip and pinch maximums

4.13 Results Summary

Based on the average number of parameters within ±5% of the criterion task, the simulation which best estimated the demand of the criterion task was that with real parts and simple feedback (B). This simulation also had the highest rank correlation with the criterion task for perceived effort (0.78), and grip force matching (0.75). Using this simulation, the average perceived effort over all participants was within ±5% of the criterion task 50% of the time, grip force matching 31% of the time and EMG 75% of the time. The next best simulation was that with real parts and force and moment feedback (C) followed by the simulation with simplified parts and force and moment feedback (D).

Tasks with the best simulations were simple, static tasks with moderate forces similar to that of the criterion task. Demand determined using normative values from the literature showed a correlation of 0.56 with the criterion task (A) increasing to 0.80 for the simulation with simplified parts and simple feedback (D), a situation closer to that in which the normative data was collected.

Hypothesis 1: There was a difference in estimated physical demand between the criterion task and the three simulations. Simulation B with real parts and simple feedback had the fewest differences compared with the criterion task followed by simulations C and then D.

Hypothesis 2: The rank order of tasks, according to the magnitude of parameters measured, was different for the most realistic version of a task compared to the simulations. Simulation B had highest average rank correlation considering perceived effort, grip force matching and EMG followed by simulation C and then D.

Hypothesis 3: The physical demand determined using normative data was different from that determined using perceived effort and grip force matching during simulations. It was most similar to the perceived effort of simulations C followed by D.

5 Discussion

The purpose of this section is to discuss sources of the difference in demand , as introduced in Table 2. While the individual contribution of these factors was not tested, they all potentially contribute to differences in demand between the criterion task and simulations. This section also covers variation due to a single repetition, comparison with normative data, fatigue, the best measurement of demand, the effect of Type I errors, and recommendations for practitioners.

5.1 Simulations with the fewest differences from the criterion task

The simulation with real parts and simple feedback (B) had a demand most similar to that of the criterion task as determined by looking at the 3 methods of comparison (ANOVA, ±5%, ICC) for each task and the rank correlation for all tasks with the criterion task for all simulations. Simulation B had the most similarities in hand-object interface to the criterion task. For example, the handle shape, size, orientation, posture and height were the same as the criterion task, leading to more similar physical demand estimates (Cadoret & Smith 1996, Dempsey & Ayoub 1996, Fischer et al. 2009, Kohl 1981, Oh & Radwin 1993, Seo et al. 2008). This simulation also had the simplest method of feedback, providing force or moment feedback in one or two directions. If an existing task with parts available was being evaluated or redesigned, this simulation would give the best estimate of demand.

In situations when tasks are being designed with no physical prototypes or parts, simulation D is likely the one which would be used to estimate demand. While this was not the most accurate simulation, it did have 75% of perceived effort, 70% of grip force matching and 85% of EMG within ±10% of the criterion task.

Take home message: The simulation with real parts and simple feedback (B) best represented the criterion task.

5.2 Using visual feedback to match forces and moments

For simulations with force and moment feedback, participants were required to use visual feedback to match forces and moments in 6 directions (Simulations C and D). If a participant was within ±10% of the non-zero force and moment targets and close to zero for others, they were considered to be applying the required forces and moments.

Participants were not always able to reach the required targets while maintaining all other forces and moments close to zero. For example, if the upward force was high (Task 1: Sledge hammer hold) participants may not have been able to maintain the required upward force and radial deviator moment while maintaining all other forces and moments near zero. As well, if the forces and moments were low (Task 17: Fastener initiation extended posture) some participants were not able to match them. This could be due in part to the visual resolution of the system which, for extremely low forces and moments, limited the accuracy.

Take home message: Using visual feedback to match extremely high or low forces and moments was difficult and contributed to differences in estimated demand between the most realistic version of a task and its simulations.

5.3 Dynamic compared with static tasks

Several of the most realistic tasks were dynamic, for example, the radiator hose insertion (Task 5). Higher muscle activation than the static simulations was seen. A possible source of this difference is the method with which the average insertion force used for the simulations was determined. For the radiator hose insertion force (Task 5), the average insertion force was determined by repeatedly measuring the researcher's average insertion force with a hand-held force transducer. This method is similar to that used in the automotive industry by ergonomists who use their own insertion forces to estimate mechanical demand. If a participant was using a higher or lower insertion force for the criterion task, this could have caused differences in task demand compared to the simulations. Simulations might be more representative of the most realistic version of each dynamic task if each participant's average insertion force had been used to develop the simulations. This would not be very helpful in practice.

There was variation in force, speed and posture over the course of dynamic criterion tasks. For example, the radiator hose insertion force for the criterion task started at zero, increased to a maximum and then decreased (Task 5, Appendix A). Insertion speed was not regulated and Drinkhaus, Armstrong & Faulke (2009) noted that an insertion speed increase from 5.1 to 38.1 mm/s resulted in a 39% increase in axial force, a possible source of differences compared to static simulations. Changes in posture magnify concerns with EMG measurement, such as the non-linear variation of the force-length relationship of muscle fibres, the changing distance between electrodes and active muscles fibres, and changes in grip force over the course of a task (DeLuca 1997, Maier Hepp-Raymond 1995, Werremeyer & Cole 1999). These differences between dynamic criterion tasks and their simulations are another source of the differences in estimated demand.

Take home message: In this research, static simulations of dynamic tasks underestimated task demand.

5.4 Maximum compared with average force

For dynamic tasks, the averaged forces required were measured. For example, the average force required to insert the wire harness connectors (Tasks 13 & 14) was 14.9N while the peak force was 39.5N, see

Figure 15. This average force was used to develop simulations of these tasks and participants were required to hold this force for 5s during collection. Using the average force, reduced the time required for data collection by minimizing the training required before participants could reach the force and minimizing recovery because the force was lower. Casey et al. (2002) found that study participants matching a grip force underestimated the peak force by 45.4% and the average force by only 4.8%, indicating they were matching the average grip force required to perform a task. Village et al. (2005) found peak spinal compression was better correlated with perceived effort. This offers one explanation for the higher perceived effort measured for the dynamic criterion task, compared to simulations based on the average force (Village et al. 2005).

Take home message: Using the average force to simulate a dynamic manual task may have underestimated perceived effort.

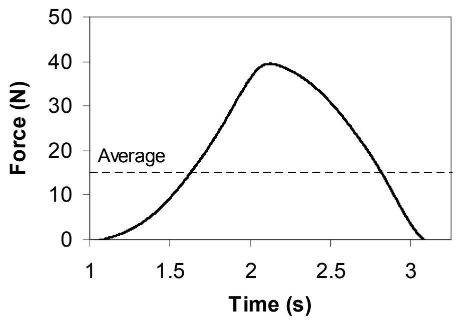


Figure 15: Comparison of the average and maximum push force required to insert the radiator hose (Task 5)

5.5 Changes in mental demand

Performing simulations with simple feedback required matching forces in one or two directions (Simulation B). These tasks may have had a different mental demand than simulations that required matching forces and moments in 6 directions (Simulations C and D). Greig (2001) found that participants were able to match multiple force or moment feedback signals accurately. Au & Keir (2005) found that when study participants performed a maximal grip exertion while performing a mental task, their maximum grip strength decreased by 7%MVC. When participants were performing two exertions at once, a shoulder exertion during a maximal grip exertion, their maximum grip strength decreased an average of 10%MVC. Requiring participants to match forces and moments in 6 directions may have increased the mental demand of some simulations, making it more difficult for participants to match all 6 forces and moments. This may have caused a higher or lower demand than the criterion task (A), depending on whether participants applied too much or too little force. An increase in control has also been associated with an increase in muscle activation (Fisher, Wells & Dickerson 2009). Some of the tasks investigated in this research showed higher muscle activation for more highly controlled simulations (C and D) but this was not consistent across all tasks.

Take home message: Using visual feedback to match forces and moments in 6 directions likely increased the mental demand of the task and made it more difficult to apply appropriate forces and moments. This may have increased participants perceptions of effort.

5.6 Hybrid grips

5.7

The wire harness connector with wires (Task 13) was classified as a modified lateral pinch task. For this task with real parts, participants had to modify their lateral pinch to include a power grip to accommodate the wires in the palm of the hand (Table 34). For the version of this task without wires (Task 14), a clearly defined lateral pinch was used. The use of a hybrid lateral pinch-power grip did not cause participants to estimate a higher or lower pinch force compared to simulations with clearly defined pinches.

Take home message: Tasks with hybrid grips and pinches did not over or underestimate grip force matching in this study.

Table 34: Comparison of grip force matching for the wire harness connectors with wires, requiring a modified lateral pinch and without

	Modified Lateral Pinch		Lateral Pinch	
	Task 13: Wire harness connector with wires	%MVC	Task 14: Wire harness connector without wires	%MVC
Simulation A:		**56.4**		**56.1**
Simulation C:		**38.5**		**29.1**
Simulation D:		**30.3**		**44.6**

5.8 Maximal moments vs. maximum grips and pinches

Participants resistance to maximum moments applied to the hand was used to elicit maximum voluntary electrical activity in this research. Some tasks requiring a pinch grip had extremely low muscle activation. For example, Task 17 was a fastener initiation requiring a pulp pinch in an extended posture with low extensor digitorum (ED) activation (8.7%MVE). Pinch grip force production depends on the largely unmeasured intrinsic hand musculature rather than the measured extrinsic forearm muscles. A maximum pinch grip will therefore produce low extrinsic muscle activity (Figure 16). If the electrical activity for this pinch task had been normalized to the maximum elicited during a maximal pulp pinch, extensor digitorum activity would appear higher (17.4%MVE) and could be considered to better represent the relative demand of that pinch grip. Comparison with all muscles measured for this task can be seen in Figure 16, normalized to the maximum electrical activation elicited using maximum moments and the maximum pulp pinch. For tasks requiring a pinch grip, normalizing EMG to the maximum electrical activity in that pinch posture offers a different estimate of the relative activation possible in that grasp, not to the maximum possible by applying maximum moments.

Take home message: Normalizing EMG to the maximum activation in the grip used to perform that task gives a more interpretable estimate of relative demand in that grip.

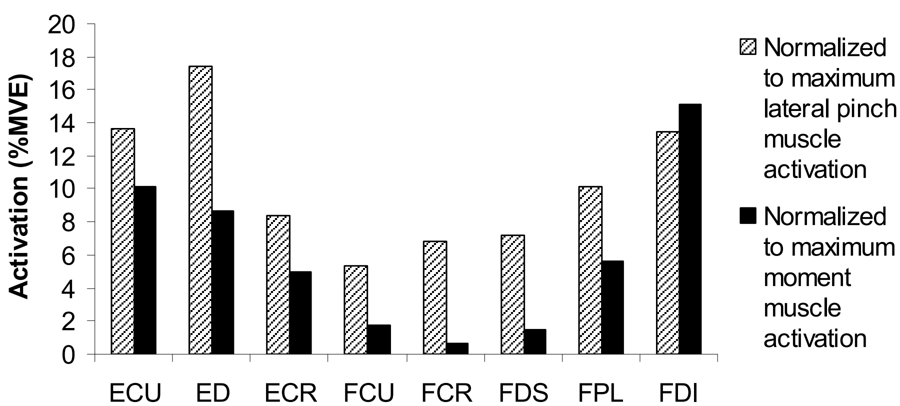


Figure 16: Pulp pinch fastener initiation in an extended posture (Task 17) to compare muscle activation using maximum moments and maximum pinches

5.9 Results of power grips compared with pinches

The average number of differences between manual tasks with grips (power and diagonal volar) and pinches (lateral and pulp) was compared to determine whether grip or pinch tasks better estimated the demand of the criterion task Results of this analysis show that grip tasks had fewer differences (Table 35) on average for all simulations.

Take home message: Pinch task simulations had more differences from the most realistic version of a task than grip tasks.

Table 35: Comparison of the average number of differences determined using repeated measures ANOVA from the criterion task for perceived effort, grip force matching, and EMG

	Grasp	Perceived effort	Grip force matching	EMG (average over all 8 muscles)
Average # of differences across all simulations	**Grip** Power & Diagonal Volar Grip	0.0	0.1	2.2
	Pinch Lateral & Pulp Pinch	0.0	0.2	2.3

5.10 Repeated trials

The number of manual tasks and simulations required an entire day of testing, preventing repetition of all tasks. Ten random tasks were repeated for all participants. Using paired t-tests, the demand measured for the two repetitions was compared at a significance level of 0.05. No significant differences were found. For two repetitions of the same task, the absolute value of the difference between the two and the percent difference were calculated and can be found in Appendix G. The average for each measured parameter is included in Table 36. Flexor carpi radialis (FCR) had the lowest average absolute difference (3%MVE) while grip force matching (Grip) had the highest (16%MVC). The lowest average percent difference was for extensor carpi radialis (ECR, 39%) while the first dorsal interossesus (FDI) had the highest (70%). The percentage difference was useful for considering the difference between repetitions of tasks with diverse magnitudes of demand. It may not be a good indicator of the difference for tasks with low demand. For example, one participant rated the perceived effort (RPE) required to push and turn the small drill (Task 12) at 0.3%Max and the second repetition as 4.1%Max. The percent difference between the two values was 172% but the absolute difference was 3.8%Max. While the percent difference is large, the absolute value of this difference is quite small.

Take home message: Though two repetitions of the same task showed no differences using a paired t-test, more repetitions would reduce within subject variability.

Table 36: Comparison of the average absolute and percent difference between two repetitions of the same task for all participants

Parameter	Units	Average Absolute Difference	Average Percent Difference (%)
RPE	(%Max)	10	58
Grip force estimate	(%MVC)	16	68
ECU	(%MVE)	7	52
ED	(%MVE)	5	47
ECR	(%MVE)	4	39
FCU	(%MVE)	4	50
FCR	(%MVE)	3	49
FDS	(%MVE)	5	50
FPL	(%MVE)	5	50
FDI	(%MVE)	9	70

5.11 Comparison with normative data

For each task, the human demand determined using perceived effort and grip force matching was correlated with the direction of largest normative demand determined using average male capability and the mechanical task demand. The correlation value was low for the criterion task (A) and the simulation with real parts and simple feedback (B). This value increased for the two simulations most similar to the normative data collection methods, the simulation with real parts (C) and simplified parts (D) with force and moment feedback. These two simulations also had the tightest control on the directions for force or moment application.

The correlation was higher for perceived effort than for grip force matching. This could be due to the fact that demand determined using grip force matching was based on grip (or pinch) alone whereas the demand based on perceived effort was due to the feeling in the hand and forearm, more representative of the physical demand required by the hand to exert forces and moments.

The relative demand determined using normative data was generally lower than that determined using perceived effort. Perceived effort reflects the loading of many structures, some of which may be more highly loaded than others. Depending on which loads are measured, perceptions may be higher than physical demand determined using normative data. In this research, using normative data to estimate manual task demand underestimated demand, possibly leading to a task that causes fatigue over a shift and increases the risk of MSD.

Normative data for the application of forces and moments with various grip types is not commonly available. While grip and pinch force strength has been well studied and normative data of this type is common, it is not easily connected to physical demand, unless the task requires a simple squeeze without external forces or moments acting (Wells and Greig 2001). For example, Tasks 13 and 14, are smooth, plastic wire harness connectors that require a high lateral pinch force to exert a relatively low axial connection force. The pinch force may overestimate task demand compared to the axial push force. Another example where grip force is not representative of physical demand concerns curved parts that fit into the palm of the hand. Task 18 involved hose insertions using a modified lateral pinch. This task involved a hose that was pinched by the fingers and extended through the palm, facilitating the application of a push force by the palm as well as the pinch. The demand determined using this modified pinch would be anticipated to be lower than that determined using a lateral pinch without modification. Grip strength alone does not take into account the push force generated by other parts of the hand in the modified lateral pinch scenario. While grip strength is one aspect of demand, the force or moments applied while using a particular grip are necessary to determine physical demand. Normative data of this type is not always readily available.

Take home message: Normative data, when available, is useful for physical demand estimates considering one direction of force or moment application. It is less representative of the demand in complex tasks or grips.

5.12 Fatigue

Across all muscles, there was an average decrease in mean power frequency of 1.2% (±0.05%) from the reference task at the beginning of testing compared with the end of testing. Using the original mean power frequencies, a paired sample t-test ($p<0.05$) was performed. There were no significant differences found in the mean power frequency between the reference task at the beginning and end of the protocol for any of the muscles examined

Take home message: There was no detectable muscle fatigue over the day.

5.13 Demand Estimators

The ranking of tasks was compared between each measured parameter to determine whether any one parameter better predicted the rank of that parameter for the criterion task. More details can be found in Appendix G. The average highest correlation between the ranking of the criterion task (A) and all simulations was for perceived exertion (0.74) and grip force matching (0.73). Of all the muscles under examination, the highest rank correlation between the criterion task and the average of all simulations was for extensor digitorum activation (0.68). Flexor carpi ulnaris , flexor carpi radialis and the first dorsal interosseus had slightly lower rank correlations (all 0.64).

Individual measurements of perceived exertion and grip force matching were quite variable, for example 75 our of 86 tasks had higher standard deviation for perceived effort or grip force matching compared to any of the 8 EMG channels. Despite this within and between participant variation, both perceived effort and grip force matching are capable of estimating the demand for an appropriate number of participants (Casey et al. 2002). For example, Petersson et al. (2000) found good accuracy for rating mechanical exposure at the group level but poor precision. Using perceived exertion to determine demand has been found to be more accurate when participants are trained to estimate perceived exertion using 3 benchmarks. This procedure, which was used in this study, has been shown to decrease estimation error by approximately 20%MVC at moderate forces (Marshall, Armstrong & Ebersole, 2004).

In an occupational setting, the use of perceived effort may be subject to some limitations. For example, a person may systematically rate a task higher or lower depending on intrinsic factors such as strength, or extrinsic factors. In this research, participants did not have any reason for rating tasks differently than their perception of the effort required. They were hired for 8 hours to perform this research and they did not have a long term interest in the tasks. In an occupational setting, if workers were asked to repeatedly rate the effort required to perform a small number of tasks, they may remember their rating between repetitions, negating the effect of multiple trials. This research required participants to perform each criterion task only once, with simulations of that task interspersed randomly throughout the testing period, removing this influence on perceived effort.

Take home message: Ranking task simulations using perceived effort, grip force matching, or EMG is comparable to the ranking of the criterion.

5.14 Task Based Analysis: Type I Error

This research is based on 11 participants and required differences between means to be significant at the 0.05 level. With analysis of variance using multiple tests there is a chance of experiment-wise Type I errors, causing rejection of the null hypothesis when this is not actually the case. In this research, rejection of the null hypothesis due to Type I errors caused differences between the criterion task and simulations of that task, making simulations less representative of the most realistic version of a task. Alternatives to this method of comparison (i.e. determining whether parameters were within ±5% of the criterion task) gives an alternative view not subject to this type of error.

Take home message: Multiple tests leading to Type I errors may result in simulations that appear less representative of the most realistic version of a task

5.15 Recommendations for practitioners trying to estimate hand and forearm demand in occupational settings

The findings of this study suggest to the following recommendations for simulating manual tasks:

- Use a simulation with the same handle size, shape, orientation and posture as the task of interest
- More complex tasks with non-zero forces and moments in more directions are more likely to have a different demand when simulated.
- As using the average force underestimated the demand in simulations of dynamic tasks, when simulating dynamic tasks, consider simulations based on the peak force or matching the force profile rather than the average force.
- Simulations of tasks requiring a power grip likely give better demand estimates than those requiring a pinch grip.
- If EMG is being used as an estimator of demand, consider using extensor digitorum, flexor carpi ulnaris, flexor carpi radialis or the first dorsal interosseous. In addition, normalize the EMG amplitude to the maximum activation elicited in the grip required to perform the task of interest to estimate the relative capability in that grip.
- Perceived effort and grip force matching best match the demand required by the criterion task. These measures were subject to large variability, which would require the use of multiple people and multiple trials to estimate task demand.
- As most normative data reports maximum grip or pinch forces only, rather than exerting external forces and moments, it is often difficult to directly compare a task demand measured as an external force or moment with normative data from the literature. Unless the task demands have a dominant grip requirement, the use of grip or pinch force only will give misleading demand estimates. The data set published by Greig and Wells (2004) may be more relevant for most tasks.
- The more similarities there are between the conditions under which the normative data was collected and the task of interest, the better the estimated demand. Demand estimated using normative data often underestimates that of the task of interest.

5.16 Example: Simulating the tasks of a Medical Sonographers

One goal of this research was to determine how different ways of simulating manual tasks affected the estimate of demand on the hand and forearm. This research has shown that simulating a task with real parts with simple feedback (B) and real parts with force and moment feedback (C) can be representative of a more realistic simulation of that task. Diagnostic medical sonographers use ultrasound as a diagnostic tool. Repetitive and dynamic movements are required to manipulate the transducer on the body. These movements have been associated with scanning-related disorders, for example carpal tunnel symptoms (Schoenfeld et al. 1999). In order to determine the human demand of scanning, this task could be simulated in the laboratory. The peak exerted force used by experienced sonographers could be measured using a hand held force transducer attached to a scanner during scanning. A simulation in the laboratory could be developed that requires holding a real scanner handle and pushing with the appropriate force. Simple feedback in one direction could be used to ensure the correct force is applied. These conditions are similar to those required for the simulation with real parts and simple feedback (B) which was the simulation with the most similar demand compared to the criterion task. Measurement of the perceived effort, and estimated grip force could then be used to estimate the demand required to perform this task.

Take home message: When simulating manual tasks, consider using real parts with simple feedback (forces or moments in 1 or directions) or real parts with force and moment feedback (6 directions).

5.17 Limitations

This study is not without limitations. The insertion forces used for some manual tasks were determined using an average of those forces required by the researcher to perform the task multiple times. For example, Task 5 required the insertion of a radiator hose onto a radiator. Over 30 insertions with 3 different exercised hoses were used to determine the average insertion force and to develop the static simulations. This is one factor that may have contributed to the higher demand determined for dynamic criterion tasks compared to static simulations. Using the peak force as measured by the researcher rather than the average may have increased the demand of the simulations, making them more similar to the criterion task. This method is representative of methods used in industry but it may not represent the forces or techniques used by participants, causing additional differences in measured demand between the criterion task and the task's simulations. Measuring each participants average force and using those forces to develop simulations, might have led to fewer differences between the most realistic version of a task and that task's simulations. This would have required more of each participants time and the measured forces would still be quite variable, depending on the method used to measure that participant's forces with a force transducer.

Another limitation of this work is the single performance of each task by each participant. While there were no significant differences between two repetitions of 10 random tasks, this is a source of within-subject variation that could be reduced by using 2 or 3 repetitions of each task. The increased variability due to a single performance of each task would make this data less likely to show differences between simulation types.

The use of EMG to measure the electrical activity of hand and forearm muscles is subject to some limitations. The small size of muscles in close proximity and the limited surface area overlying them means that cross-talk is probable (Mogk & Keir 2003). Careful placement of electrodes based on the fine wire insertion recommendations made by Zipp (1982) and comparison of the signal generated by the muscle of interest during isometric contractions with other muscles was used to minimize crosstalk.

The direction of largest normative demand was compared with perceived effort and grip force matching for each task. Ignoring the demand required by other directions of force and moment application is a limitation of this comparison between the normative data and the criterion task and simulations. Use of a model incorporating all direction of force and moment application might result in more similarities between normative demand and task demand (Wells, Greig & Ishac 2007).

5.18 Future Work

A comparison of these simulations with the on-line task upon which the simulated tasks were based is necessary to validate the use of simulations to measure manual task demand. Possible limitations include the use of exercised parts for this research in comparison with un-exercised parts used on the assembly line. This might result in higher forces and moments for the on-line task and subsequently a higher demand.

5.19 Discussion Summary

The simulation with real parts and simple feedback (B) best represented the criterion task. This simulation had the most similarities in hand-object interface, such as size, shape, orientation, posture, and height, as the criterion task and required feedback in only 1 or 2 directions. As simulations became more controlled, there was a greater difference from the criterion task. Using visual feedback to match extremely high forces and moments was difficult for participants, the easiest tasks were those requiring moderate forces, (typically 20-40%MVC). This may be a source of the difference in demand between the most realistic version of a task and that task's simulations. Static simulations tended to underestimate the demand of dynamic manual tasks. This could be due to the use of the average force required by the task used in the simulations, rather than the peak force, a limitation of this research.

The use of visual feedback of forces and moments in 6 directions may have increased the mental demand of the simulations making it more difficult for participants to apply the correct forces and moments in all directions. The use of hybrid grips, for example a lateral pinch with a simultaneous power grip, had a similar grip force matching magnitude compared to the same task with an unambiguous lateral pinch.

Power grip tasks had fewer differences from the criterion task than pinch tasks. When examining manual tasks requiring a pinch grip, a better idea of the task demand may be obtained by normalizing EMG to the maximum activation elicited in the pinch of interest rather than that elicited using maximal moments. Repeating all tasks more than once would have decreased variation, a limitation of this research. Demand determined using normative data tended to underestimate that of the criterion task and had the highest correlation with perceived effort.

Task ranking using perceived effort and grip force matching appeared to have the highest correlation with the rank of the most realistic version of all tasks, followed by extensor digitorum activation. Type I error due to multiple tests would cause differences between tasks not due to demand. Alternative methods of comparison were also used that were not prone to this error.

The results of this research can be used to make recommendations to practitioners trying to estimate hand and forearm demand in an occupational setting.

6 Conclusions

The purpose of this research was to determine how different ways of simulating manual tasks affected the estimates of physical demand on the hand and forearm system and to determine how well normative data estimated physical demand. The following are the main conclusions derived from this research:

- Changes in handle size, shape, orientation, posture, feedback and task complexity from the criterion task affected the estimates of demand on the hand and forearm, from a small to moderate degree.
- Static simulations based on the average force required for a dynamic manual task underestimated demand, underestimating the fatigue that may result if this task were performed over an entire shift or the potential for injury.
- Tasks with hybrid grips and pinches had similar demand estimates to tasks with unambiguous grips and pinches.
- Pinch task simulations had a poorer demand estimate than power grip tasks.
- Using extensor digitorum as a representative muscle and normalizing EMG to the maximum activation measured in the same grasp as that used to perform the tasks better estimated relative activation.
- Demand determined using normative data based on the dominant task component, underestimated the demand required to perform a manual task and was more highly correlated with the more controlled simulations C and D.
- Over the wide variety of tasks used here, perceived effort and grip force matching appeared to provide the best demand estimates. However they were subject to a larger variation within and between individuals than other methods, necessitating the use of multiple trials and multiple raters.

This research shows that it is possible to estimate demand based on a simulation of a realistic version of a manual task and to estimate demand using normative data from the literature. The more different the real task is from the situation in which the forces and moments were measured, the larger the discrepancy in demand estimates. Practitioners and researchers making estimates of physical demand on the hand and forearm based upon simulations or normative literature values should consider the effects of these factors. Recommendations for simulating and measuring demand of occupational tasks developed in this thesis should enable practitioners to identify manual tasks which may exceed the capability of segments of the population, may lead to fatigue over a shift, or increase the risk of injury to the upper limb. These recommendations are intended to help practitioners minimize these outcomes.

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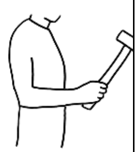
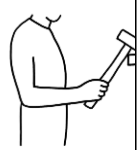
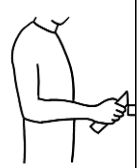
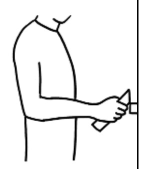
Appendix A

Determining the forces and moments required to perform each real task

Task	Method of Force and/or Moment Measurement				
1 Sledge hammer hold	 **Static task** ▪ Diagonal volar grip ▪ Constant upward force: measured mass of hammer 20.0N ▪ Constant radial deviator moment: mass acting 0.29m from centre of mass, 5.73Nm ▪ 1 non-zero force, 1 non-zero moment				
	Most Realistic A	**Simulation C**	**Simulation D1**	**Simulation D2**	**Simulation D3**
					
	Criterion task: Real hammer hold Vertical force: 20N Radial deviator moment: 5.73Nm	**Real parts with force and moment feedback:** Hammer hold simulated with a hammer fixed at 45° to force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a 35mm handle fixed at 45° to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

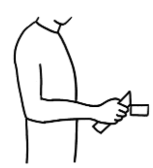
2
22 oz hammer hold

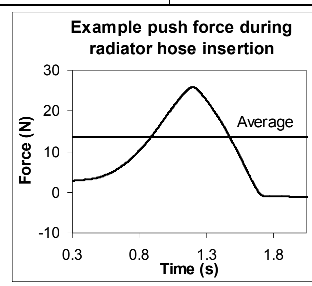
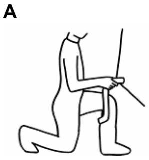
Static task
- Diagonal volar grip
- Constant upward force: measured mass of hammer 10.0N
- Constant radial deviator moment: mass acting 0.20m from centre of mass, 1.95Nm
- 1 non-zero force, 1 non-zero moment

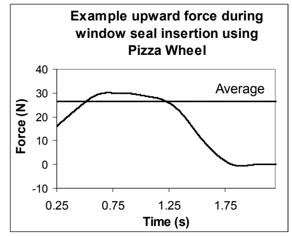
Most Realistic A	Simulation C	Simulation D1	Simulation D2	Simulation D3
				
Criterion task: Real hammer hold Vertical force: 10N Radial deviator moment: 1.95Nm	**Real parts with force and moment feedback:** Hammer hold simulated with a hammer fixed at 45° to force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated a 35mm handle fixed at 45° to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

3
16 oz hammer hold

Static task
- Constant upward force: measured mass of hammer 7.2N
- Constant radial deviator moment: mass acting 0.13m from centre of mass, 0.93Nm
- 1 non-zero force, 1 non-zero moment

Most Realistic A	Simulation C	Simulation D1	Simulation D2	Simulation D3
				
Criterion task: Real hammer hold Vertical force: 7.2N Radial deviator moment: 0.93Nm	**Real parts with force and moment feedback:** Hammer hold simulated with a hammer fixed at 45° to force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated a 35mm handle fixed at 45° to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

4 Modified heavy hammer hold hammer		**Static task** ▪ Constant upward force: measured mass of hammer 83.0N ▪ Constant radial deviator moment: mass of hammer head acting 0.20m from centre of mass, 1.95Nm ▪ 1 non-zero force, 1 non-zero moment ▪ 1 non-zero force, 1 non-zero moment			
	Most Realistic A 	**Simulation C** 	**Simulation D1** 	**Simulation D2** 	**Simulation D3** 
	Criterion task: Real modified hammer hold Vertical force: 83N Radial deviator moment: 1.20Nm	**Real parts with force and moment feedback:** Hammer hold simulated with a hammer fixed at 45° to force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated a 35mm handle fixed at 45° to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer	**Simplified parts with force and moment feedback:** Hammer hold simulated with a 35mm vertical handle fixed to a force transducer
5 Radiator hose insertion		**Dynamic task** ▪ Upward force: measured mass of radiator hose 3.43N ▪ Push force: force required to insert hose, 13.5N ▪ 2 non-zero forces ▪ Average of 10 insertions			
	Most Realistic A 	**Simulation B** 	**Simulation C** 	**Simulation D2** 	**Simulation D3** 
	Criterion task: Push radiator hose onto real radiator Push force: 13.5N Vertical force: 3.43N	**Real parts with simple feedback:** Radiator hose attachment simulated with a constant force	**Real parts with force and moment feedback:** Radiator hose attachment simulated with a hose attached a to force transducer	**Simplified parts with force and moment feedback:** Radiator hose attachment simulated with a horizontal 35mm handle fixed to a force transducer	**Simplified parts with force and moment feedback:** Radiator hose attachment simulated with a vertical 35mm handle fixed to a force transducer

<table>
<tr>
<td rowspan="3">6
Window seal insertion using pizza wheel</td>
<td colspan="4">
Dynamic task
▪ Upward force: force required to insert window seal 25.6N
▪ Average of 10 insertions
▪ Dorsal force: horizontal force required to insert window seal 10.0N
▪ 2 non-zero forces

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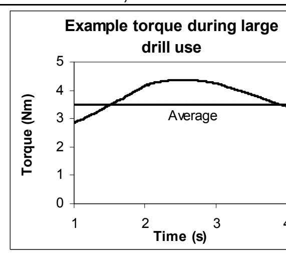
<tr>
<td>Most Realistic A
</td>
<td>Simulation B
</td>
<td>Simulation C
</td>
<td>Simulation D4
</td>
</tr>
<tr>
<td>Criterion task: Insert window seal into car door

Vertical force: 25.6N

Dorsal force: 10.0N</td>
<td>Real parts with simple feedback: Push up and right against constant force</td>
<td>Real parts with force and moment feedback: Window seal insertion with pizza wheel fixed to a force transducer</td>
<td>Simplified parts with force and moment feedback: Window seal insertion simulated with a 25mm handle perpendicular to the axis of the forearm fixed to a force transducer</td>
</tr>
</table>

<table>
<tr><td>7
Large Drill hold</td><td></td><td colspan="3">Static task
Constant upward force: measured mass of drill 23.2N
1 non-zero force</td></tr>
<tr><td>8
Large drill
hold and push</td><td></td><td colspan="3">Static task
Constant upward force: measured mass of drill 23.2N
Push force: force estimate 5N
2 non-zero forces</td></tr>
<tr><td>9
Large drill hold,
push, torque</td><td></td><td colspan="3">Static task
Constant upward force: measured mass of drill 23.2N
Constant push force: force estimate 5N
Constant pronator moment: measured maximum torque of drill 3.5Nm
2 non-zero forces, 1 non-zero moment</td></tr>
<tr><td rowspan="3">Large Drill Simulations</td><td colspan="4">
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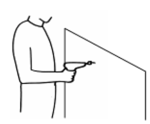
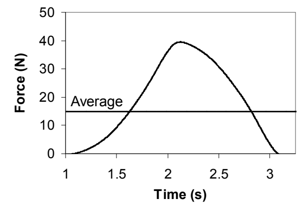
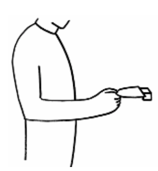
<tr><td>Most Realistic A
</td><td>Simulation B
</td><td>Simulation C
</td><td>Simulation D4
</td></tr>
<tr><td>Criterion task: Hold, push or torque drill

Vertical force: 23.12N
Push force: 5N
Pronator moment: 3.5Nm</td><td>Real parts with simple feedback: Hold, push or torque drill while aiming at a specific target</td><td>Real parts, visual feedback: Simulated drill hold, push or torque with drill fixed to a force transducer</td><td>Simplified parts, visual feedback: Simulated drill hold push or torque with a 25mm handle fixed to a force transducer</td></tr>
</table>

10 Small drill hold		**Static task** ▪ Constant upward force: measured mass of drill 7.4N ▪ 1 non-zero force
11 Small drill hold and push		**Static task** ▪ Constant upward force: measured mass of drill 7.4N ▪ Constant push force: force estimate, 5N ▪ 2 non-zero forces
12 Small drill hold, push and torque		**Static task** ▪ Constant upward force: measured mass of drill 7.4N ▪ Constant push force: force estimate 5N ▪ Constant pronator moment: measured maximum torque of drill, 3.0Nm ▪ 2 non-zero forces, 1 non-zero moment

Small Drill Simulations	**Most Realistic A** 	**Simulation B** 	**Simulation C** 	**Simulation D4** 
	Criterion task: Hold, push or torque drill Vertical force: 7.35N Push force: 5N Pronator moment: 3.0Nm	**Real parts with simple feedback:** Hold, push or torque drill while aiming at a specific target	**Real parts with force and moment feedback:** Simulated drill hold, push or torque with drill fixed to a force transducer	**Simplified parts with force and moment feedback:** Simulated drill hold push or torque with a 25mm handle fixed to a force transducer

<table>
<tr><td>13
Wire harness connector (ORC1 Wires)</td><td></td><td colspan="2">Dynamic task
▪ Push force: force required to insert connector 15.0N
▪ 1 non-zero force
▪ Average of 10 trials
▪ Modified lateral pinch</td><td rowspan="2">
</td></tr>
<tr><td>14
Wire harness connector (ORC2 no wires)</td><td></td><td colspan="2">Dynamic task
▪ Push force: force required to insert connector, 15.0N
▪ 1 non-zero force
▪
▪ Average of 10 trials
▪ Standard lateral pinch</td></tr>
<tr><td rowspan="2">Wire harness connector simulations
</td><td>Most Realistic A
</td><td>Simulation B
</td><td>Simulation C
</td><td>Simulation D4
</td></tr>
<tr><td>Criterion task: Push to attach wire harness to connector

Push force: 15.0N</td><td>Real parts with simple feedback: Push wire harness against resistance</td><td>Real parts with force and moment feedback: Simulated wire harness push with a wire harness fixed to a force transducer</td><td>Simplified parts with force and moment feedback: Simulated wire harness push with a 25mm handle fixed to a force transducer</td></tr>
<tr><td>15 Plate 0.5kg</td><td></td><td colspan="3">Static task
▪ Constant upward force: measured mass of light plate 6.9N
▪ Constant radial deviator moment: mass acting 0.085m from pinch 0.58Nm
▪ 1 non-zero force, 1 non-zero moment</td></tr>
<tr><td>16 Plate 2.2kg</td><td></td><td colspan="3">Static task
▪ Constant upward force: measured mass of heavy plate 23.5N
▪ Constant radial deviator moment: mass acting 0.085m from pinch 2.0Nm
▪ 1 non-zero force, 1 non-zero moment</td></tr>
<tr><td rowspan="2">Plate Hold Simulations</td><td>Most Realistic A
</td><td>Simulation B
</td><td>Simulation C
</td><td>Simulation D4
</td></tr>
<tr><td>Criterion task: Hold plate</td><td>Real parts with simple feedback: Hold plate with constant hanging mass</td><td>Real parts with force and moment feedback: Simulate plate hold with a plate fixed to a force transducer</td><td>Simplified parts with force and moment feedback: Simulate plate hold with a 25mm handle fixed to a force transducer</td></tr>
</table>

<table>
<tr>
<td rowspan="4">17
Fastener Initiation extended posture</td>
<td colspan="4">
Dynamic task
▪ Bolt wrapped with 6cm of Teflon tape to increase force/moment required
▪ Supinator moment:: required to turn nut on bolt 0.03Nm
▪ Push force: force required to push nut onto bolt while turning 1.0N
▪ 1 non-zero force, 1 non-zero moment
▪ Average of 7 trials</td>
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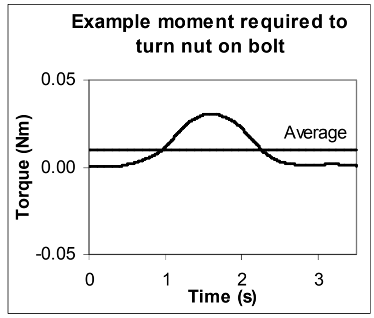
<td colspan="4">
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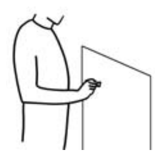
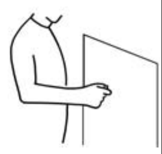
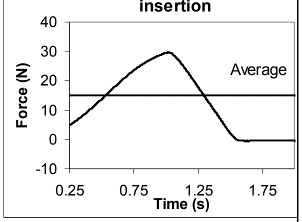
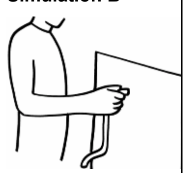
<tr>
<td>Most Realistic A
</td>
<td>Simulation B
</td>
<td>Simulation C
</td>
<td>Simulation D6
</td>
</tr>
<tr>
<td>Criterion task: Rotate nut on bolt

Push force: 0.98N

Supinator moment: 0.03Nm</td>
<td>Real parts with simple feedback: Rotate nut against constant force and moment</td>
<td>Real parts with force and moment feedback: Nut rotation simulated with a nut fixed to a force transducer</td>
<td>Simplified parts with force and moment feedback: Nut rotation simulated with a 25mm handle parallel to the axis of the forearm fixed to a force transducer</td>
</tr>
</table>

Task	Most Realistic A	Simulation B	Simulation C	Simulation D5	Simulation D6
18 Fastener initiation neutral posture		**Dynamic task** ▪ Bolt wrapped with 6cm of Teflon tape to increase force/moment required ▪ Force/moment data from Task 17 used here ▪ 1 non-zero force, 1 non-zero moment			
					
	Criterion task: Turn nut on bolt, with neutral posture Push force: 0.98N Supinator moment: 0.03Nm	**Real parts with simple feedback:** Turn nut in neutral posture against constant force and moment	**Real parts with force and moment feedback:** Nut turn in neutral posture simulated with a nut fixed to a force transducer	**Simplified parts with force and moment feedback:** Nut rotation in neutral posture simulated with a 25mm handle parallel fixed to a force transducer	**Simplified parts with force and moment feedback:** Nut rotation in neutral posture simulated with a 25mm fixed to a force transducer

Task	Most Realistic A	Simulation B	Simulation C	Simulation D4
19 Power steering hose insertion		**Dynamic task** ▪ Upward force: measure mass of hose 1.47N ▪ Push force: force required to insert hose 16.0N ▪ Average of 10 trials ▪ 2 non-zero forces ▪ Modified lateral pinch		 Example push force during power steering hose insertion
				
	Criterion task: Insert hose on radiator Push force: 16.0N Vertical force: 1.47N	**Real parts with simple feedback:** Push hose against constant force	**Real parts with force and moment feedback:** Hose insertion simulated with a hose fixed to a force transducer	**Simplified parts with force and moment feedback:** Hose insertion simulated with a 25mm handle fixed to a force transducer

<table>
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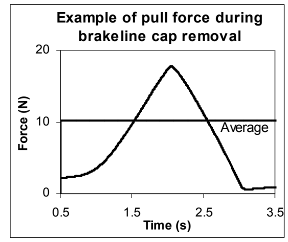
<td rowspan="4">20
Brake line cap removal</td>
<td colspan="5">
Dynamic task
▪ Pull force: force required to remove brake line cap 10.2N
▪ 1 non-zero force
</td>
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<tr>
<td>Most Realistic A</td>
<td>Simulation B</td>
<td>Simulation C</td>
<td>Simulation D7</td>
<td>Simulation D6</td>
</tr>
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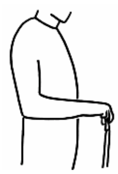
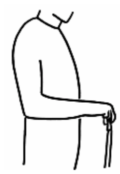
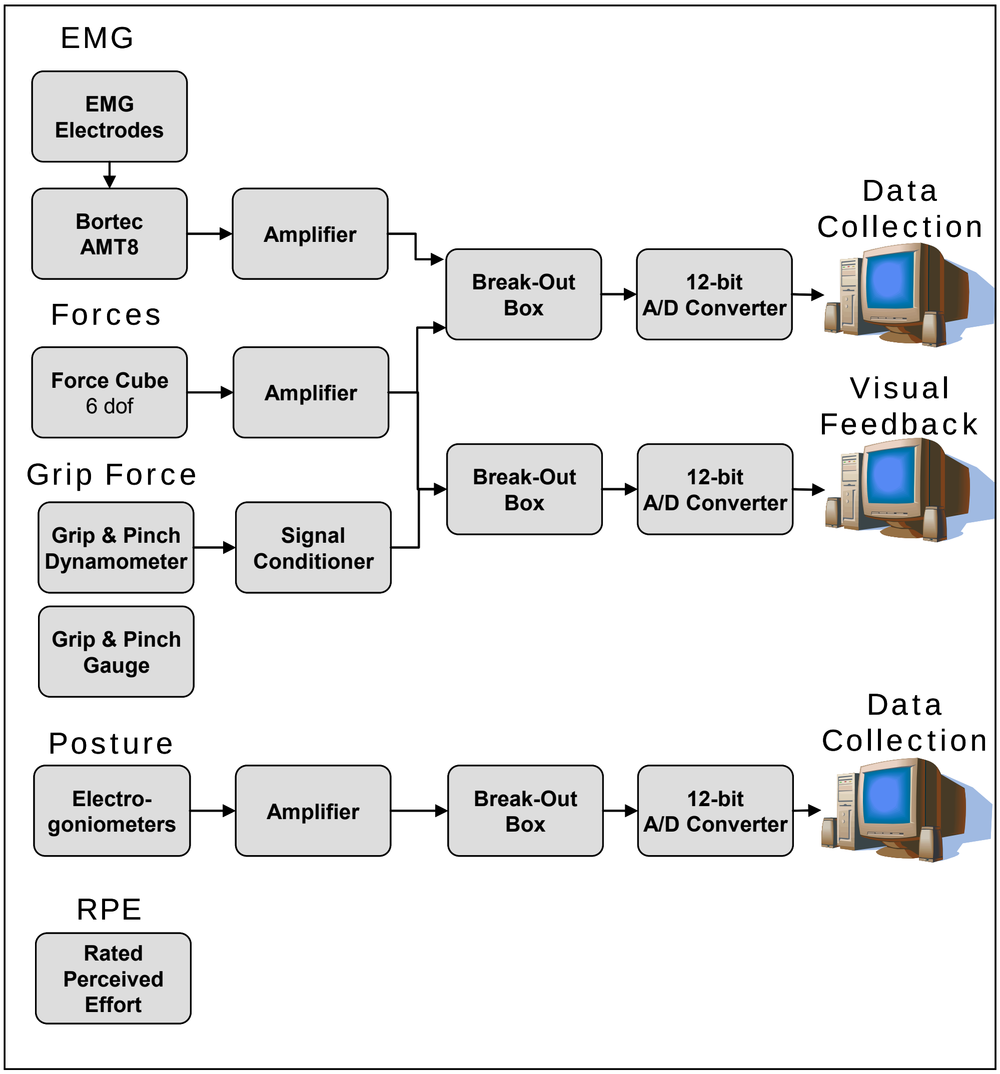
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion task: Pull brake line cap from brake line

Pull force: 10.2N</td>
<td>Real parts with simple feedback: Cap pull simulated with a constant force</td>
<td>Real parts with force and moment feedback: Cap pull simulated with a cap attached to a force transducer</td>
<td>Simplified parts with force and moment feedback: Cap pull simulated with a vertical 25mm handle fixed to a force transducer</td>
<td>Simplified parts with force and moment feedback: Cap pull simulated with a horizontal 25mm handle fixed to a force transducer</td>
</tr>
</table>

Appendix B

Block Diagram of Set-Up

Block Diagram of Set-Up

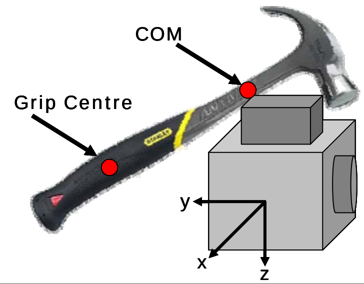


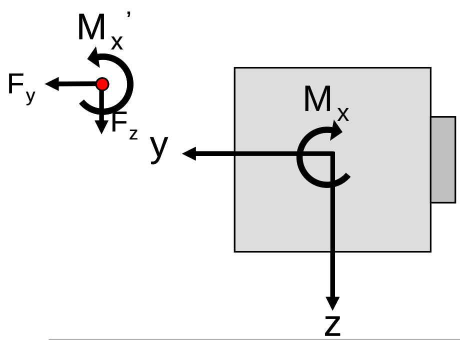
Appendix C

Moment Correction Equations

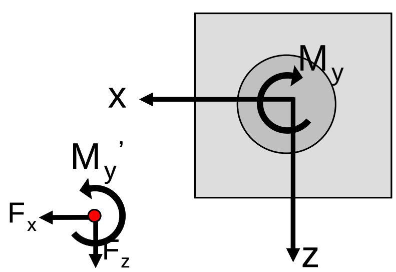
Moment Correction Equations

Moment Correction

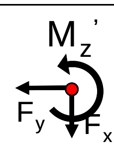


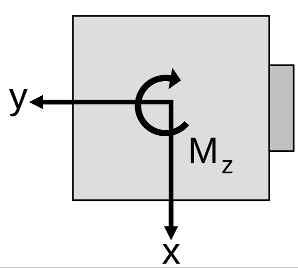


$$\sum M_x = 0$$
$$0 = M_x - M_x' + F_y d_z - F_z d_y$$
$$M_x' = M_x + F_y d_z - F_z d_y$$



$$\sum M_y = 0$$
$$0 = M_y - M_y' - F_x d_z + F_z d_x$$
$$M_y' = M_y - F_x d_z + F_z d_x$$





$$\sum M_z = 0$$
$$0 = M_z - M_z' + F_y d_x - F_x d_y$$
$$M_z' = M_z - F_x d_y - F_y d_x$$

Appendix D

Summary of numerical individual task results

Table D1: Numerical results of Task 1 – Sledge hammer hold

		A	C	D1	D2	D3
Perceived Effort	(%Max)	27.6	44.8	38.7	40.6	43.2
Grip	(%MVC)	27.7	33.3	33.0	35.7	29.8
ECU	(%MVE)	18.2	34.7	35.2	30.4	47.0
ED	(%MVE)	24.6	35.9	38.3	33.5	44.6
ECR	(%MVE)	15.4	26.6*	25.7*	27.3	26.5*
FCU	(%MVE)	9.6	10.6	8.6	12.7	8.1
FCR	(%MVE)	7.8	7.7	8.1	9.5	11.6
FDS	(%MVE)	11.6	13.2	14.4	17.4	15.0
FPL	(%MVE)	14.3	26.2	27.7*	31.9*	38.3*
FDI	(%MVE)	19.0	31.5	17.8	24.4	43.5*
Uln/Rad Dev	+Uln (º)	15	15.3	28.4	22.7*	43.0*
Pro/Sup	+Pro (º)	10	10.1	18.7	29.5*	-17.1
Flex/Ex	+Flex (º)	-42	-41.8	-37.8	-15.6	-7.0
Upward force	(N)	20.0	20.0 ± 5.4	19.4 ± 8.4	18.4 ± 8.4	19.2 ± 5.5
Radial deviator moment	(Nm)	5.73	4.63 ± 1.67	3.99 ± 1.44	4.32 ± 1.88	3.67 ± 1.56

* Indicates significant difference from the criterion task (A) p < 0.05

Table D2: Numerical results of Task 2 – 22oz hammer hold

		A	C	D1	D2	D3
Perceived Effort	(%Max)	19.1	28.6	24.6	22.8	29.2
Grip	(%MVC)	14.5	24.5*	18.4	17.3	19.8
ECU	(%MVE)	11.2	15.7*	16.4	12.8	25.7*
ED	(%MVE)	10.4	16.8*	16.0*	14.7*	21.2*
ECR	(%MVE)	7.2	12.0*	9.4	9.6	11.0*
FCU	(%MVE)	7.0	8.1	8.9	7.4	5.3
FCR	(%MVE)	4.7	5.5	4.7	4.2	6.2
FDS	(%MVE)	6.3	8.8	8.4	8.3	9.0
FPL	(%MVE)	6.4	12.6*	12.8*	11.7*	17.6*
FDI	(%MVE)	5.9	10.6	10.9	9.0	20.8
Uln/Rad	+Uln (º)	14.7	21.0	29.1	48.1*	-12.2*
Pro/Sup	+Pro (º)	0.1	19.3	12.0	-14.6	20.6*
Flex/Ex	+Flex (º)	-36.5	-36.5	-31.1	-6.2	-56.5
Upward force	(N)	10.0	10.6 ± 3.4	10.0 ± 4.0	9.9 ± 3.9	12.1 ± 1.6
Radial deviator moment	(Nm)	1.95	1.85 ± 0.61	1.57 ± 0.58	1.81 ± 0.64	1.54 ± 0.59

* Indicates significant difference from the criterion task (A) p < 0.05

Table D3: Numerical results of Task 3 – 16oz hammer hold

		A	C	D1	D2	D3
Perceived Effort	(%Max)	11.9	17.9	21.1	21.1	22.3
Grip	(%MVC)	9.0	10.4	12.5	16.3	20.4*
ECU	(%MVE)	6.4	8.3	7.2	7.1	13.0*
ED	(%MVE)	5.5	8.3	10.3	7.3	10.6
ECR	(%MVE)	5.5	6.7	7.1	6.4	6.1
FCU	(%MVE)	4.5	4.8	5.3	4.7	3.5
FCR	(%MVE)	3.3	3.5	3.4	3.3	3.8
FDS	(%MVE)	4.5	6.4	5.4	5.8	5.9
FPL	(%MVE)	4.3	6.3	7.5	7.8	9.2*
FDI	(%MVE)	3.3	3.5	5.2	6.6	7.3
Uln/Rad Dev	+Uln (º)	28.1	23.8	26.4	46.2*	-7.7*
Pro/Sup	+Pro (º)	-4.7	11.4	1.2	-12.3	9.9
Flex/Ex	+Flex (º)	-36.1	-46.0	-30.9	-11.3*	-55.8
Upward force	(N)	7.20	9.14 ± 1.29	8.00 ± 1.26	7.82 ± 1.15	8.23 ± 1.18
Radial deviator moment	(Nm)	0.93	1.10 ± 0.35	0.94 ± 0.15	0.97 ± 0.24	0.86 ± 0.20

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D4: Numerical results of Task 4 – Modified heavy hammer hold

		A	C	D1	D2	D3
Perceived Effort	(%Max)	60.1	52.8	56.3	59.4	49.7
Grip	(%MVC)	39.4	32.6	32.2	39.4	33.5
ECU	(%MVE)	30.1	31.7	33.3	26.3	46.1*
ED	(%MVE)	51.5	35.3*	33.4*	31.7*	42.0
ECR	(%MVE)	62.9	44.3	44.7	40.9	42.0
FCU	(%MVE)	22.2	19.1	14.3*	22.4	9.5*
FCR	(%MVE)	21.2	15.0*	12.5*	12.7*	13.3
FDS	(%MVE)	34.7	20.4*	19.7*	19.4*	19.9*
FPL	(%MVE)	46.5	28.4	27.3	23.6*	31.7
FDI	(%MVE)	31.6	23.2	20.5	13.6	23.4
Uln/Rad Dev	+Uln (º)	22.3	31.0	27.6	56.0*	0.2*
Pro/Sup	+Pro (º)	-2.3	14.0	-4.1	-7.9	19.6
Flex/Ex	+Flex (º)	-19.7	-30.6	-21.6	-3.0	-44.4*
Upward force	(N)	83.0	62.3 ± 21.7	66.5 ± 16.8	68.1 ± 19.0	63.2 ± 25.0
Radial deviator moment	(Nm)	1.95	1.36 ± 1.57	1.31 ± 1.50	1.63 ± 0.77	1.06 ± 1.23

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D5: Numerical results of Task 5 – Radiator hose insertion

		A	B	C	D2	D3
Perceived Effort	(%Max)	20.6	18.2	19.1	14.9	13.3
Grip	(%MVC)	18.9	17.6	17.3	14.1	14.2
ECU	(%MVE)	11.4	4.5*	6.4*	6.0*	5.8*
ED	(%MVE)	7.6	4.2*	5.9	7.4	4.2*
ECR	(%MVE)	12.8	3.2*	3.6	4.3	3.2*
FCU	(%MVE)	5.9	3.1*	3.1*	4.5	2.6*
FCR	(%MVE)	5.5	1.5*	2.2*	2.3*	1.5*
FDS	(%MVE)	5.7	2.6*	3.4	3.4	3.4*
FPL	(%MVE)	10.3	3.1*	5.4*	5.5	3.7*
FDI	(%MVE)	3.9	1.8	4.3	3.0	1.8*
Uln/Rad Dev	+Uln (º)	17.9	20.4	48.4*	50.6*	3.9
Pro/Sup	+Pro (º)	-11.7	-18.8	-17.7	-11.3	4.6
Flex/Ex	+Flex (º)	-37.3	-26.0	-23.3	-4.4*	-48.2
Upward force	(N)	13	13	12.8 ± 1.32	12.5 ± 1.22	12.6 ± 1.15
Push force	(N)	3.43	3.43	4.85 ± 1.25	5.06 ± 1.46	4.81 ± 0.85

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D6: Numerical results of Task 6 – Window seal insertion using pizza wheel

		A	B	C	D3
Perceived Effort	(%Max)	37.5	29.5	30.0	26.9
Grip	(%MVC)	36.7	27.1	18.1*	18.9*
ECU	(%MVE)	29.4	17.4	8.2*	10.5
ED	(%MVE)	23.3	12.6	6.0*	7.5*
ECR	(%MVE)	26.6	15.0	8.5*	11.5
FCU	(%MVE)	24.5	7.8*	5.5*	7.2*
FCR	(%MVE)	22.2	8.3*	7.6*	9.4
FDS	(%MVE)	24.7	11.2*	8.7*	9.5
FPL	(%MVE)	27.4	11.0	6.8*	8.6
FDI	(%MVE)	27.6	5.6*	3.5*	3.2*
Uln/Rad Dev	+Uln (º)	11.6	11.5	10.4	2.4
Pro/Sup	+Pro (º)	-11.4	9.7	3.8	7.3
Flex/Ex	+Flex (º)	-30.7	-50.5	-34.0	-19.1
Upward force	(N)	26	26	24.5 ± 8.0	28.4 ± 10.4
Dorsal force	(Nm)	10	10	7.9* ± 3.4	9.1 ± 2.2

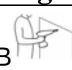
* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D7: Numerical results of Task 7 – Large drill hold

		A 	B 	C 	D3 
Perceived Effort	(%Max)	23.2	28.6	22.7	22.0
Grip	(%MVC)	21.1	14.7	18.5	18.9
ECU	(%MVE)	12.6	11.3	10.1	9.4
ED	(%MVE)	11.6	12.8	11.7	6.5
ECR	(%MVE)	10.7	12.6	11.4	9.0
FCU	(%MVE)	6.6	6.5	4.9	4.2
FCR	(%MVE)	5.5	5.6	3.9	4.1
FDS	(%MVE)	9.2	8.7	7.0	5.4
FPL	(%MVE)	8.8	9.2	8.6	7.4
FDI	(%MVE)	4.1	3.5	6.4	2.2
Uln/Rad Dev	+Uln (º)	8.5	3.9	10.1	4.9
Pro/Sup	+Pro (º)	13.2	8.2	14.0	1.6
Flex/Ex	+Flex (º)	-34.7	-33.9	-31.3	-40.3
Upward force	(N)	23	23	22.7 ± 4.0	21.9 ± 5.0

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D8: Numerical results of Task 8 – Large drill push

		A 	B 	C 	D3 
Perceived Effort	(%Max)	27.3	21.4	26.6	21.2
Grip	(%MVC)	17.2	17.4	23.5	15.7
ECU	(%MVE)	16.0	12.5	8.0*	9.6*
ED	(%MVE)	14.7	13.9	8.3*	6.8*
ECR	(%MVE)	12.0	10.9	9.0*	8.2*
FCU	(%MVE)	5.0	5.2	6.2	4.7
FCR	(%MVE)	4.2	4.2	3.7	4.0
FDS	(%MVE)	7.0	8.0	7.6	4.9
FPL	(%MVE)	10.1	9.0	7.2	7.1
FDI	(%MVE)	3.5	3.4	2.7	2.4
Uln/Rad Dev	+Uln (º)	-2.1	5.8	10.4	5.9
Pro/Sup	+Pro (º)	25.1	-2.1	5.9	10.6
Flex/Ex	+Flex (º)	-38.1	-27.3	-45.9	-47.2
Upward force	(N)	23	23	22.7 ± 3.2	21.9 ± 7.9
Push force	(N)	5	5	5.5 ± 0.6	4.9 ± 2.1

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D9: Numerical results of Task 9 – Large drill push & torque

		A	B	C	D3
Perceived Effort	(%Max)	34.3	31.5	37.7	41.2
Grip	(%MVC)	33.8	31.0	27.4	28.5
ECU	(%MVE)	9.6	11.3	25.6*	25.3
ED	(%MVE)	12.2	15.3	14.4	13.8
ECR	(%MVE)	8.9	9.9	12.7	15.7
FCU	(%MVE)	11.2	13.0	15.9	13.4
FCR	(%MVE)	9.0	8.3	16.2	15.5
FDS	(%MVE)	10.8	12.0	18.3	20.3
FPL	(%MVE)	11.7	15.1	18.1	19.1
FDI	(%MVE)	9.3	9.6	14.7	19.5
Uln/Rad Dev	+Uln (º)	-3.8	-1.0	14.5*	5.2*
Pro/Sup	+Pro (º)	-5.7	14.5	33.9	0.3
Flex/Ex	+Flex (º)	-43.0	-35.4	-28.0	-58.1
Upward force	(N)	23	23	25.7 ± 3.2	23.3 ± 7.9
Push force	(N)	5	5	5.8 ± 0.6	5.4 ± 2.1
Pronator moment	(Nm)	3	3	3.3 ± 0.6	2.8 ± 0.6

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D10: Numerical results of Task 10 – Small drill hold

		A	B	C	D3
Perceived Effort	(%Max)	17.5	14.3	17.4	13.9
Grip	(%MVC)	18.2	12.7	10.7	7.6
ECU	(%MVE)	7.9	7.9	6.1	5.6
ED	(%MVE)	6.7	7.4	5.6	4.9
ECR	(%MVE)	6.0	6.3	5.6	4.7
FCU	(%MVE)	4.0	3.6	2.8	2.9
FCR	(%MVE)	3.5	3.4	2.7	2.3
FDS	(%MVE)	4.4	4.6	5.2	3.2
FPL	(%MVE)	5.3	5.1	5.1	4.7
FDI	(%MVE)	2.5	1.8	4.1	2.4
Uln/Rad Dev	+Uln (º)	2.9	1.7	2.4	5.8
Pro/Sup	+Pro (º)	-3.2	5.2	6.2	7.9
Flex/Ex	+Flex (º)	-45.1	-45.5	-37.9	-42.3
Upward force	(N)	7.4	7.4	9.2 ± 2.8	8.4 ± 2.0

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D11: Numerical results of Task 11 – Small drill push

		A	B	C	D3
Perceived Effort	(%Max)	24.8	14.8	13.4*	16.4
Grip	(%MVC)	19.9	11.3	9.8*	8.9*
ECU	(%MVE)	8.6	5.7	3.9	5.9
ED	(%MVE)	7.1	5.8	3.6	4.7
ECR	(%MVE)	5.4	4.7	4.4	3.7
FCU	(%MVE)	3.5	2.9	2.5	4.2
FCR	(%MVE)	2.5	2.1	2.3	2.3
FDS	(%MVE)	3.6	3.1	2.9	4.3
FPL	(%MVE)	4.4	4.8	4.2	5.0
FDI	(%MVE)	1.9	1.5	1.3	2.1
Uln/Rad Dev	+Uln (º)	-3.9	-4.2	1.1	3.4
Pro/Sup	+Pro (º)	7.2	18.5	8.2	-1.7
Flex/Ex	+Flex (º)	-44.3	-35.9	-41.8	-41.1
Upward force	(N)	7.4	7.4	9.5 ± 0.7	9.4 ± 0.9
Push force	(N)	5	5	5.2 ± 3.8	4.9 ± 1.2

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D12: Numerical results of Task 12 – Small drill push & torque

		A	B	C	D3
Perceived Effort	(%Max)	29.8	23.9	38.0	33.6
Grip	(%MVC)	34.6	23.0	29.5	28.6
ECU	(%MVE)	12.9	9.8	21.7	22.4
ED	(%MVE)	12.7	13.9	13.9	10.0
ECR	(%MVE)	8.6	7.4	9.7	8.5
FCU	(%MVE)	11.7	11.6	15.2	12.5
FCR	(%MVE)	7.1	7.0	16.3*	13.1*
FDS	(%MVE)	10.7	11.6	17.8*	14.1*
FPL	(%MVE)	10.6	13.4	15.7*	16.1*
FDI	(%MVE)	7.2	11.3	13.1	16.3
Uln/Rad Dev	+Uln (º)	-8.6	-6.3	-0.4	10.9*
Pro/Sup	+Pro (º)	-2.4	-7.2	25.1*	14.8
Flex/Ex	+Flex (º)	-37.1	-40.3	-44.6	-42.7
Upward force	(N)	7.4	7.4	10.0 ± 4.4	7.1 ± 10.0
Push force	(N)	5	5	5.6 ± 1.8	4.4 ± 1.2
Pronator moment	(Nm)	3	3	2.9 ± 0.8	2.5 ± 0.5

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D13: Numerical results of Task 13 – Wire harness connector ORC1 (wires)

		A	B	C	D4
Perceived Effort	(%Max)	25.8	21.0	24.7	26.4
Grip	(%MVC)	56.4	38.5*	30.3*	45.2
ECU	(%MVE)	19.8	5.1	11.3	10.4
ED	(%MVE)	10.0	4.1	4.9	5.4
ECR	(%MVE)	7.5	2.4	3.1	6.0
FCU	(%MVE)	7.4	1.6*	3.1	4.8
FCR	(%MVE)	8.6	1.4*	5.8	4.5
FDS	(%MVE)	9.2	1.9*	4.5	4.2
FPL	(%MVE)	11.0	3.9*	6.5	8.5
FDI	(%MVE)	5.8	2.9*	6.1	4.2
Uln/Rad Dev	+Uln (º)	30.5	28.7	31.5	13.3*
Pro/Sup	+Pro (º)	-26.0	-26.3	-26.6	-27.6
Flex/Ex	+Flex (º)	-22.4	-20.0	-28.0	-44.9
Push force	(N)	15	15	13.1 ± 5.0	11.7 ± 6.2

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D14: Numerical results of Task 14 – Wire harness connector ORC2 (no wires)

		A	B	C	D4
Perceived Effort	(%Max)	27.8	24.0	31.0	20.5
Grip	(%MVC)	56.1	29.1*	44.6*	34.7*
ECU	(%MVE)	19.1	8.1*	11.6*	7.8*
ED	(%MVE)	8.9	4.6*	5.4*	3.4*
ECR	(%MVE)	6.4	2.6*	3.4*	2.8*
FCU	(%MVE)	7.1	1.5*	3.4*	2.9*
FCR	(%MVE)	7.6	2.2*	5.2*	4.0*
FDS	(%MVE)	7.4	2.1*	4.9	3.4*
FPL	(%MVE)	11.8	4.5*	8.3	7.5
FDI	(%MVE)	9.6	3.6	5.7	5.1
Uln/Rad Dev	+Uln (º)	24.4	19.7	14.6	10.2
Pro/Sup	+Pro (º)	-23.8	-16.2	-25.1	-34.5
Flex/Ex	+Flex (º)	-16.3	-31.8	-16.3	-16.3
Push force	(N)	15	15	14.4 ± 1.1	14.1 ± 0.7

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D15: Numerical results of Task 15 – Plate hold 0.5kg

		A	B	C	D4
Perceived Effort	(%Max)	21.3	19.1	25.3	28.9
Grip	(%MVC)	33.6	41.0	40.5	44.8
ECU	(%MVE)	14.1	8.9	9.4	19.0
ED	(%MVE)	5.0	3.8	5.3	9.6*
ECR	(%MVE)	5.5	3.8	5.1	6.2
FCU	(%MVE)	3.9	2.6	4.5	7.1*
FCR	(%MVE)	7.0	4.8	8.0	10.0
FDS	(%MVE)	7.2	5.1	6.6	9.9
FPL	(%MVE)	10.1	6.4	11.8	22.6
FDI	(%MVE)	8.6	5.8	7.6	12.1
Uln/Rad Dev	+Uln (º)	16.9	8.7	6.2	1.8*
Pro/Sup	+Pro (º)	-31.5	-31.7	-20.2	-26.5
Flex/Ex	+Flex (º)	-34.9	-26.7	-21.4	-32.4
Upward force	(N)	6.9	6.9	7.8 ± 1.23	6.8 ± 1.40
Radial deviator moment	(Nm)	0.6	0.6	0.06 ± 0.12	0.35 ± 0.17

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D16: Numerical results of Task 16 – Plate hold 2.2kg

		A	B	C	D4
Perceived Effort	(%Max)	48.7	43.2	32.1	54.2
Grip	(%MVC)	55.9	59.3	49.5	59.9
ECU	(%MVE)	33.8	28.4	26.5	40.3
ED	(%MVE)	16.5	13.1	14.0	20.7
ECR	(%MVE)	14.3	10.2	13.0	14.8
FCU	(%MVE)	10.8	9.9	14.4	20.5*
FCR	(%MVE)	18.2	14.9	18.9	27.9
FDS	(%MVE)	19.3	13.7	18.0	23.7
FPL	(%MVE)	31.9	23.9	26.7	35.3
FDI	(%MVE)	21.2	15.4	15.7	30.7
Uln/Rad Dev	+Uln (º)	2.3	10.8	-2.9	0.9
Pro/Sup	+Pro (º)	-21.6	-21.7	-4.8	-16.9
Flex/Ex	+Flex (º)	-29.5	-31.5	-20.6	-19.5
Upward force	(N)	24	24	26.6 ± 9.0	22.2 ± 5.6
Radial deviator moment	(Nm)	2	2	0.20 ± 1.21	1.12 ± 0.58

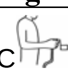
* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D17: Numerical results of Task 17 – Fastener initiation extended posture

		A 	B 	C 	D6 
Perceived Effort	(%Max)	13.5	12.2	23.0	14.0
Grip	(%MVC)	21.1	35.2	36.5	30.7
ECU	(%MVE)	10.6	5.8*	8.5	9.9
ED	(%MVE)	8.3	3.9*	5.0	7.4
ECR	(%MVE)	4.6	2.4*	3.4*	4.3
FCU	(%MVE)	2.4	1.6*	2.5	1.8*
FCR	(%MVE)	3.3	1.5*	2.0*	2.2*
FDS	(%MVE)	3.5	2.2*	3.0	2.6*
FPL	(%MVE)	8.0	5.0*	7.2	5.4*
FDI	(%MVE)	4.5	2.7	4.3	2.9
Uln/Rad Dev	+Uln (º)	10.1	25.5	26.1	16.8
Pro/Sup	+Pro (º)	6.4	-33.2*	-27.2	22.0
Flex/Ex	+Flex (º)	-40.0	-37.7	-47.7	-74.6
Palmar force	(N)	0.95	0.95	0.69 ± 0.51	1.13 ± 0.34
Ulnar moment	(Nm)	0.03	0.03	0.119 ± 0.183	-0.050 ± 0.073

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D18: Numerical results of Task 18 – Power steering hose insertion

		A 	B 	C 	D4 
Perceived Effort	(%Max)	31.7	20.9*	25.1	18.9*
Grip	(%MVC)	46.7	36.6	32.6	36.4
ECU	(%MVE)	25.8	7.0*	12.5	14.1*
ED	(%MVE)	9.6	4.4*	7.4	4.2*
ECR	(%MVE)	13.6	2.7*	4.1*	3.4*
FCU	(%MVE)	19.9	2.1*	3.3*	4.2*
FCR	(%MVE)	33.8	1.7*	5.2*	4.9*
FDS	(%MVE)	27.3	2.4*	4.8*	4.0*
FPL	(%MVE)	16.6	4.0*	6.2*	5.8*
FDI	(%MVE)	19.6	8.6	3.9	6.5
Uln/Rad Dev	+Uln (º)	3.4	20.7	36.5	8.6
Pro/Sup	+Pro (º)	-20.3	-19.1	-14.3	-14.2
Flex/Ex	+Flex (º)	6.9	-43.7*	-39.1*	-43.9*
Upward force	(N)	1.5	1.5	3.4± 2.37	1.5 ± 1.60
Push force	(N)	16	16	13.9 ± 4.98	14.9 ± 1.15

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D19: Numerical results of Task 19 – Fastener initiation neutral posture

		A	B	C	D5	D6
Perceived Effort	(%Max)	10.9	21.8	15.2	10.4	15.8
Grip	(%MVC)	30.7	40.2	32.4	25.4	28.0
ECU	(%MVE)	11.9	8.7	3.6*	7.1	7.6
ED	(%MVE)	6.6	4.7	2.6*	5.5	4.5
ECR	(%MVE)	4.6	2.6	2.1	3.5	2.7
FCU	(%MVE)	3.5	2.0	2.3	2.0*	3.2
FCR	(%MVE)	4.5	1.8*	2.5*	2.2*	2.5
FDS	(%MVE)	5.6	2.7*	2.4*	2.9*	3.3
FPL	(%MVE)	9.8	6.1	4.3	5.2	6.0
FDI	(%MVE)	11.5	5.1	3.6	4.4*	4.6
Uln/Rad Dev	+Uln (º)	12.1	37.9*	30.7	1.1	28.4
Pro/Sup	+Pro (º)	-8.2	-28.1	-39.6	3.9	-27.2
Flex/Ex	+Flex (º)	-21.2	-21.0	-3.8	-51.7	-16.5
Palmar force	(N)	1	1	1.09 ± 1.36	-1.19 ± 0.77	-0.34 ± 0.94
Supinator moment	(Nm)	0.03	0.03	0.031 ± 0.04	-0.031 ± 0.12	-0.012 ± 0.12

* Indicates significant difference from the criterion task (A) $p < 0.05$

Table D20: Numerical results of Task 20 – Brake line cap removal

		A	B	C	D7	D6
Perceived Effort	(%Max)	22.8	29.3	21.0	23.6	17.2
Grip	(%MVC)	36.1	48.6	36.3	42.3	20.5
ECU	(%MVE)	20.2	18.7	16.6	14.5	10.2
ED	(%MVE)	12.4	12.5	12.1	9.8	9.6
ECR	(%MVE)	10.8	9.7	7.4	5.9	6.8
FCU	(%MVE)	6.9	5.1	3.0*	2.1*	2.1*
FCR	(%MVE)	7.8	7.1	2.9	3.7*	2.2*
FDS	(%MVE)	9.4	8.5	4.9	4.3*	4.7
FPL	(%MVE)	11.0	11.2	10.1	6.7	5.2
FDI	(%MVE)	13.2	8.2	6.2	5.9	7.6
Uln/Rad Dev	+Uln (º)	18.2	22.0	20.7	-2.4*	17.1
Pro/Sup	+Pro (º)	5.8	12.7	18.3	42.3	36.3
Flex/Ex	+Flex (º)	-24.5	-18.5	-7.0	-56.9*	6.0*
Upward force	(N)	10.2	10.2	9.45 ± 2.56	9.28 ± 1.18	9.28 ± 1.19

* Indicates significant difference from the criterion task (A) $p < 0.05$

Appendix E

Summary of individual task results

1. Sledge Hammer Hold Summary

- Apply upward force of 20N
- Apply radial deviator moment of 5.73Nm

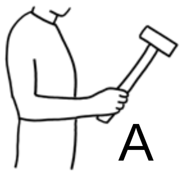


Figure E1-1: Criterion task: Real hammer hold

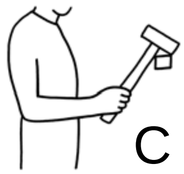


Figure E1-2: Real parts with force and moment feedback: Hammer hold simulated with a hammer fixed at 45° to force transducer

Figure E1-3: Simplified parts with force and moment feedback: Hammer hold simulated a 35mm handle fixed at 45° to a force transducer

Figure E1-4: Simplified parts with force and moment feedback: Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer

Fatigue E1-5: Simplified parts with force and moment feedback: Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

- **Forces:** Participants used feedback to match the forces and moments required to hold this hammer (Table E1-1).
- **Posture:** For the simulation with horizontal handle (D2) the wrist posture had significant more ulnar deviation and supination than the most realistic task (A). For the simulation with the vertical handle (D3) the wrist posture had significant more ulnar deviation than the most realistic simulation (A).
- **Perceived Effort:** No significant differences in perceived effort between holding a real hammer and each of the simulations were found (Figure E1-6).
- **Grip Force Matching:** No significant differences in grip force matching between holding a real hammer and simulating a hammer hold were found (Figure E1-7).
- **Muscle Activation:** Significant differences between holding a real hammer (A) and simulating a hammer hold were found with the following simulations (Figures E1-8 to E1-15):
    - o A vs. C: ECR↑
    - o A vs. D1: ECR↑, FPL↑
    - o A vs. D2: FPL↑
    - o A vs. D3: ECR↑, FPL↑, FDI↑
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real hammer hold determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E1-1: Applied forces and moments

Task	Upward Force (N)	Radial Deviator Moment (Nm)
A*	20	5.73
C	20.0 ± 5.4	4.63 ± 1.67
D1	19.4 ± 8.4	3.99 ± 1.44
D2	18.4 ± 8.4	4.32 ± 1.88
D3	19.2 ± 5.5	3.67 ± 1.56

* This task is a real hammer hold used to calculate the forces and moments required to hold a real hammer. Participants were required to match these values within +/-10%.

Intraclass Correlation Coefficients (ICC):

Table E1-2: Comparison of ICC between the criterion task and each simulation

	A-C	A-D1	A-D2	A-D3
Perceived Effort	0.42	0.36	0.18	0.16
Grip force matching	0.55	0.74	0.71	0.34
Average EMG	0.58	0.62	0.43	0.41

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Posture compared with force control

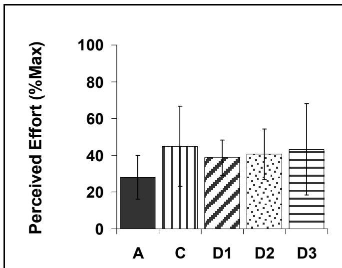


Figure E1-6: Perceived effort

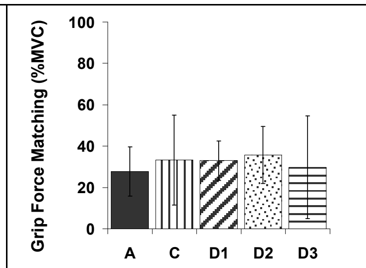


Figure E1-7: Grip force matching

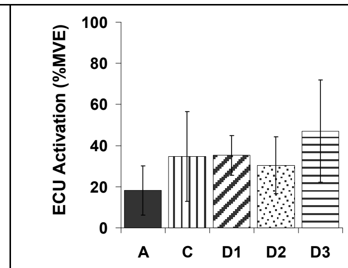


Figure E1-8: ECU %MVE

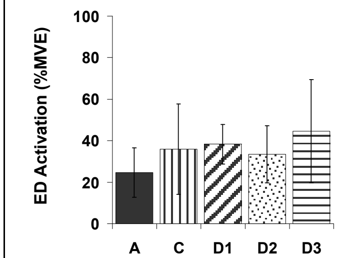


Figure E1-9: ED %MVE

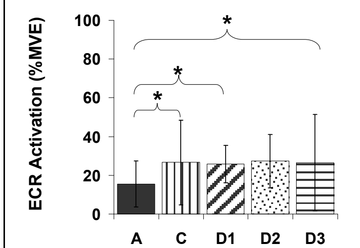


Figure E1-10: ECR %MVE

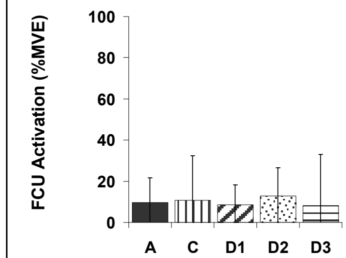


Figure E1-11: FCU %MVE

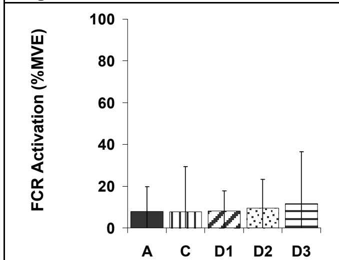


Figure E1-12: FCR %MVE

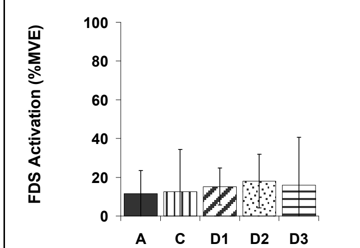


Figure E1-13: FDS %MVE

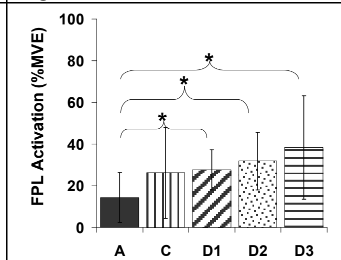


Figure E1-14: FPL %MVE

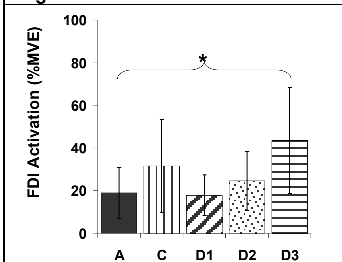


Figure E1-15: FDI %MVE

Table E1-3: Comparison of the average number of parameters within ±5% of the criterion task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	C □		D1 △		D2 ○		D3 +	
Perceived Effort	N	36%	N	27%	N	36%	N	18%
Grip	N	27%	N	27%	N	9%	Y	27%
ECU	N	36%	N	9%	N	18%	N	9%
ED	N	27%	N	0%	N	9%	N	18%
ECR	N	27%	N	27%	N	27%	N	27%
FCU	Y	73%	Y	73%	Y	64%	Y	73%
FCR	Y	82%	Y	100%	Y	73%	Y	64%
FDS	Y	64%	Y	55%	N	55%	Y	64%
FPL	N	18%	N	18%	N	9%	N	18%
FDI	N	9%	Y	36%	N	27%	N	9%
Avg EMG		42%		40%		35%		35%

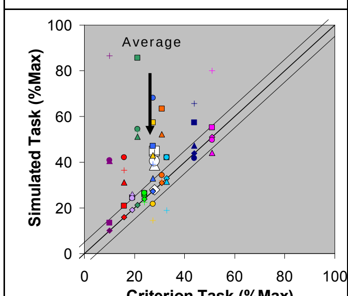


Figure E1-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

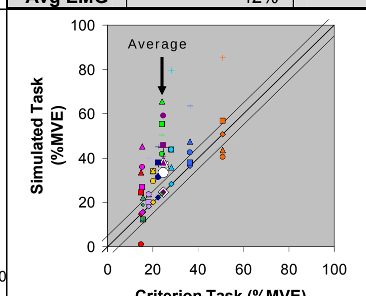


Figure E1-17: Comparison of task simulations within a ±5% range of criterion task for ED

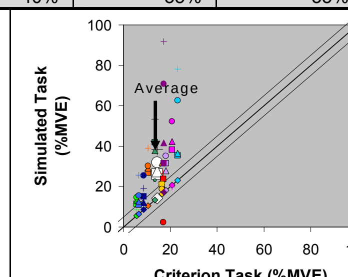


Figure E1-18: Comparison of task simulations within a ±5% range o range of criterion task for FPL

2. 22oz Hammer Hold Summary

- Apply upward force of 10 N
- Apply radial deviator moment of 1.95 Nm

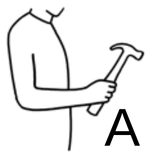


Figure E2-1: Criterion task: Real hammer hold

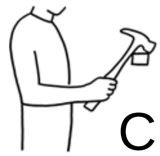


Figure E2-2: Real parts with force and moment feedback: Hammer hold simulated with hammer fixed at 45° to transducer

Figure E2-3: Simplified parts with force and moment feedback: Hammer hold simulated a 35mm handle fixed at 45° to a force transducer

Figure E2-4: Simplified parts with force and moment feedback: Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer

Figure E2-5: Simplified parts with force and moment feedback: Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to hold this hammer (Table E2-1).
- **Posture:** For the simulation with the horizontal handle (D2), the wrist posture had significant more ulnar deviation than the criterion task (A). For the simulation with the vertical handle (D3), the wrist posture had significantly more radial deviation and the forearm was more supinated than for the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort between holding a real hammer and simulating a hammer hold were found (Figure E2-6).
- **Grip Force Matching:** Participants grip force matching indicates a significantly higher grip force between a real hammer hold and holding a hammer fixed at 45º to a force cube (D1) (Figure E2-7).
- **Muscle Activation:** Significant differences between holding a real hammer (A) and simulating a hammer hold were found with the following simulations (Figures E2-8 to E2-15):
    - A vs. C: ECU↑, ED↑, ECR↑, FPL↑
    - A vs. D1: ED↑, FPL↑
    - A vs. D2: ED↑, FPL↑
    - A vs. D3: ECU↑, ED↑, ECR↑, FPL↑
- An '*' on these figures indicates a significant difference using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E2-1: Applied forces and moments

Task	Upward Force (N)	Radial Deviator Moment (Nm)
A*	10	1.95
C	10.6 ± 3.4	1.85 ± 0.61
D1	10.0 ± 4.0	1.57 ± 0.58
D2	9.9 ± 3.9	1.81 ± 0.64
D3	12.1 ± 1.6	1.54 ± 0.59

* This task is a real hammer hold used to calculate the forces and moments required to hold a real. Participants were required to match these values within +/- 10%.

Intraclass Correlation Coefficients (ICC):

Table E2-2: Comparison of ICC between the criterion task and each simulation

	A-C	A-D1	A-D2	A-D3
Perceived Effort	0.67	0.86	0.87	0.41
Grip force matching	0.65	0.37	0.85	0.27

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Posture compared with force control

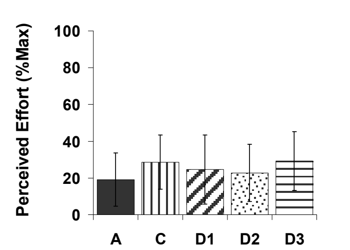


Figure E2-6: Perceived effort

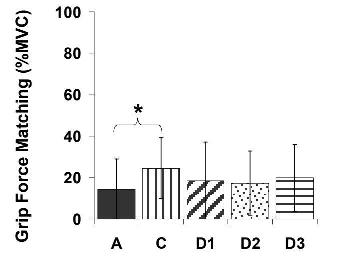


Figure E2-7: Grip strength matching

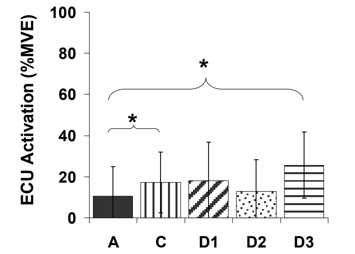


Figure E2-8: ECU %MVE

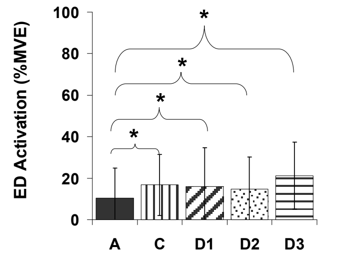


Figure E2-9: ED %MVE

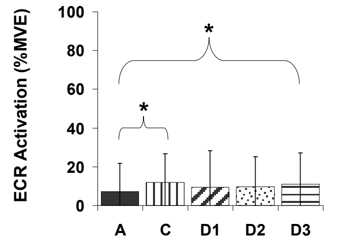


Figure E2-10: ECR %MVE

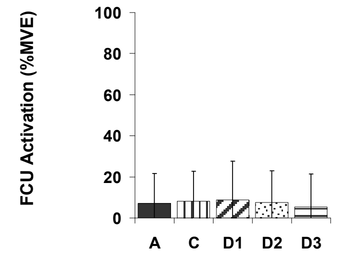


Figure E2-11: FCU %MVE

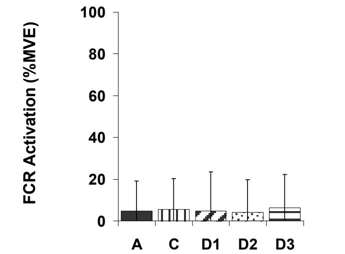


Figure E2-12: FCR %MVE

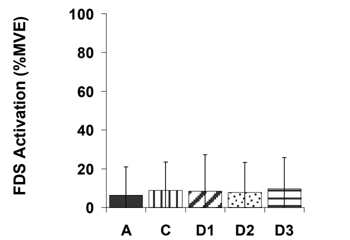


Figure E2-13: FDS %MVE

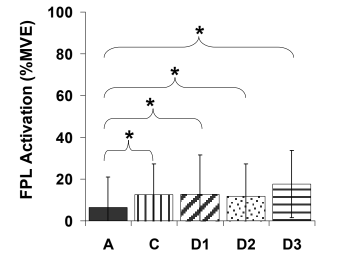


Figure E2-14: FPL %MVE

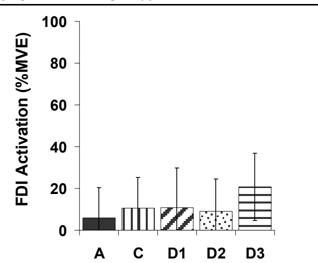


Figure E2-15: FDI %MVE

Table E2-3: Comparison of the average number of parameters within ±5% of the criterion task: Y indicates the average value of all participants' within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	C □		D1 △		D2 ○		D3 +	
Perceived Effort	N	36%	N	27%	Y	36%	N	18%
Grip	N	27%	Y	27%	Y	9%	N	27%
ECU	N	36%	N	9%	Y	18%	N	9%
ED	N	27%	N	0%	Y	9%	N	18%
ECR	Y	27%	Y	27%	Y	27%	Y	27%
FCU	Y	73%	Y	73%	Y	64%	Y	73%
FCR	Y	82%	Y	100%	Y	73%	Y	64%
FDS	Y	64%	Y	55%	Y	55%	Y	64%
FPL	N	18%	N	18%	N	9%	N	18%
FDI	Y	9%	N	36%	Y	27%	N	9%
Avg EMG		42%		40%		35%		35%

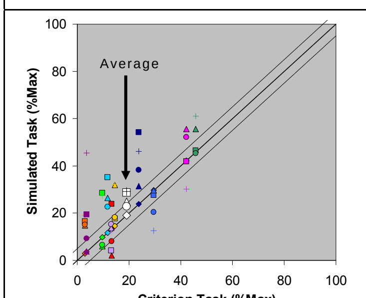


Figure E2-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

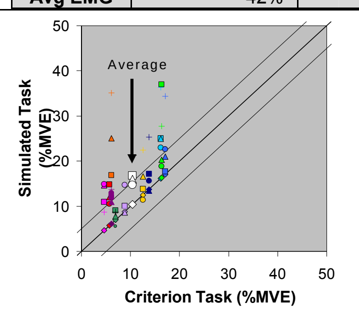


Figure E2-17: Comparison of task simulations within a ±5% range of criterion task for ED

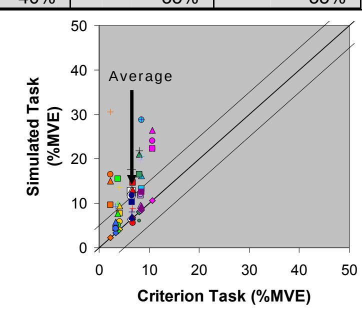


Figure E2-18: Comparison of task simulations within a ±5% range of criterion task for FPL

3. 16oz Hammer Hold Summary

- Apply upward force of 7.2N
- Apply radial deviator moment of 0.93Nm

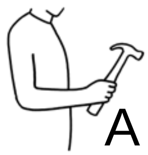


Figure E3-1: Criterion task: Real hammer hold

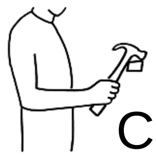


Figure E3-2: Real parts with force and moment feedback: Hammer hold simulated with a hammer fixed at 45° to force transducer

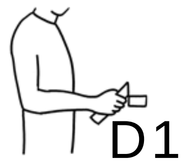


Figure E3- 3: Simplified parts with force and moment feedback: Hammer hold simulated a 35mm handle fixed at 45° to a force transducer

Figure E3- 4: Simplified parts with force and moment feedback: Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer

Figure E3- 5: Simplified parts with force and moment feedback: Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to hold this hammer (Table E3-1).
- **Posture:** For the simulation with the horizontal handle (D2) the wrist had significantly more ulnar deviation and more extension than the criterion task (A). For the simulation with the vertical handle (D3), the wrist had significantly less ulnar deviation than the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort between holding a real hammer and simulating a hammer hold were found (Figure E3-6).
- **Grip Force Matching:** Participants grip force matching indicates a significantly higher grip force between a real hammer hold (A) and the simulation with the vertical handle (D3) (Figure E3-7).

Table E3- 1: Applied forces and moments

Task	Upward Force (N)	Radial Deviator Moment (Nm)
A*	7.20	0.93
C	9.14 ± 1.29	1.10 ± 0.35
D1	8.00 ± 1.26	0.94 ± 0.15
D2	7.82 ± 1.15	0.97 ± 0.24
D3	8.23 ± 1.18	0.86 ± 0.20

* This task is a real hammer hold used to calculate the forces and moments required to hold a real hammer. Participants were required to match these values within +/-10%.

- **Muscle Activation:** Significant differences between holding a real hammer (A) and simulating a hammer hold were found with the following simulations (Figures E3-8 to E3-15):
  - A vs. C:
  - A vs. D1:
  - A vs. D2:
  - A vs. D3: ECU↑, FPL↑
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real hammer hold determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E3-2: Comparison of ICC between the criterion task and each simulation

	A-C	A-D1	A-D2	A-D3

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture and grasp type
- Different sized handle
- Different shaped handle
- Different material surface
- Posture compared with force control

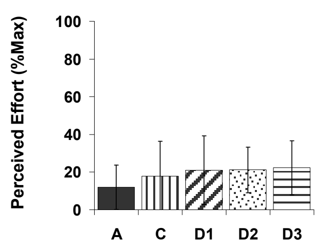


Figure E3-6: Perceived effort

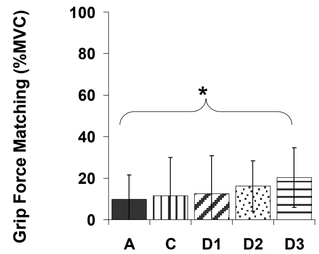


Figure E3-7: Grip strength matching

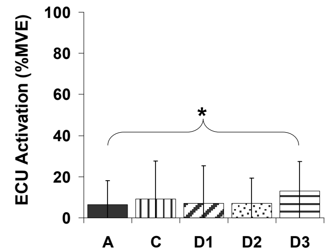


Figure E3-8: ECU %MVE

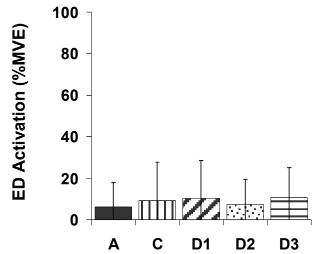


Figure E3-9: ED %MVE

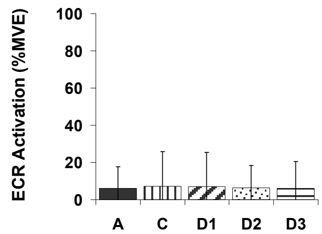


Figure E3-10: ECR %MVE

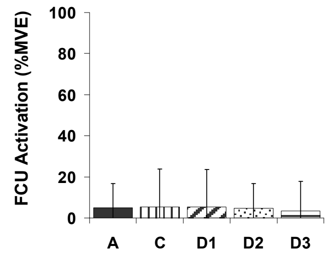


Figure E3-11: FCU %MVE

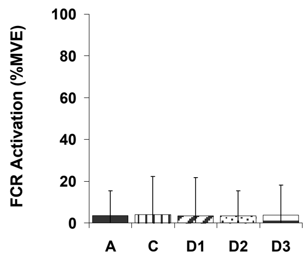


Figure E3-12: FCR %MVE

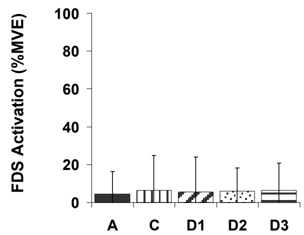


Figure E3-13: FDS %MVE

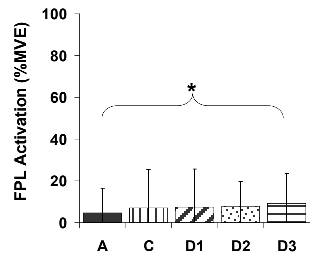


Figure E3-14: FPL %MVE

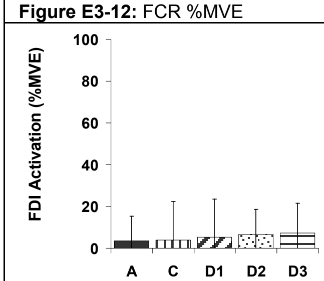


Figure E3-15: FDI %MVE

Table E3-3: Comparison of the average number of parameters within ±5% of the criterion task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	C □		D1 △		D2 ○		D3 +	
Perceived Effort	N	55%	N	27%	N	27%	N	45%
Grip	Y	73%	Y	55%	N	55%	N	18%
ECU	Y	82%	Y	82%	Y	82%	N	27%
ED	Y	64%	Y	55%	Y	82%	Y	64%
ECR	Y	82%	Y	91%	Y	82%	Y	91%
FCU	Y	73%	Y	82%	Y	100%	Y	82%
FCR	Y	100%	Y	82%	Y	91%	Y	73%
FDS	Y	82%	Y	100%	Y	82%	Y	82%
FPL	Y	73%	Y	91%	Y	82%	Y	64%
FDI	Y	100%	N	9%	Y	64%	Y	82%
Avg EMG		82%		74%		83%		70%

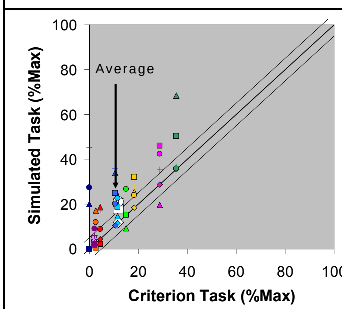


Figure E3-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

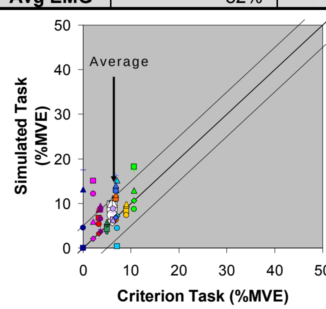


Figure E3-17: Comparison of task simulations within a ±5% range of criterion task for ED

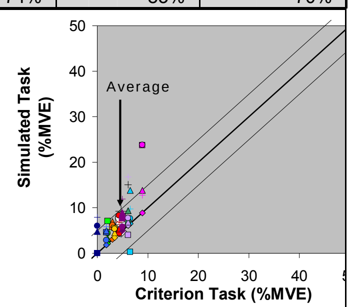


Figure E3-18: Comparison of task simulations within a ±5% range of criterion task for FPL

4. Modified Heavy Hammer Hold Summary

- Apply upward force of 83N
- Apply radial deviator moment of 1.95Nm

Figure E4-1: Criterion task: Real hammer hold

Figure E4- 2: Real parts with force and moment feedback: Hammer hold simulated with a hammer fixed at 45° to force transducer

Figure E4-3: Simplified parts with force and moment feedback: Hammer hold simulated a 35mm handle fixed at 45° to a force transducer

Figure E4-4: Simplified parts with force and moment feedback: Hammer hold simulated with a horizontal 35mm handle fixed to a force transducer

Figure E4-5: Simplified parts with force and moment feedback: Hammer hold simulated with a 35mm vertical handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to hold this hammer (Table E4-1).
- **Posture:** For the simulation with the horizontal handle (D2) the wrist had significantly more ulnar deviation than for the criterion task (A). For the simulation with the vertical handle (D3) the wrist had significantly less ulnar deviation and more extension than the criterion task (A).
- **Perceived Effort:** No significant difference in perceived effort between holding a real hammer and simulating a hammer hold with a vertical hammer was found (Figure E4-6).
- **Grip Force Matching:** No significant difference in grip force matching between holding a real hammer and simulating a hammer hold was found (Figure E4-7).

Table E4-1: Applied Forces and moments

Task	Upward Force (N)	Radial Deviator Moment (Nm)
A*	83	1.95
C	62.3 ± 21.7	1.36 ± 1.57
D1	66.5 ± 16.8	1.31 ± 1.50
D2	68.1 ± 19.0	1.63 ± 0.77
D3	63.2 ± 25.0	1.06 ± 1.23

* This task is a real hammer hold used to calculate the forces and moments required to hold a real. Participants were required to match these values within +/-10%.

- **Muscle Activation:** Significant differences between holding a real hammer (A) and simulating a hammer hold were found with the following simulations (Figures E4-8 to E4-15):
  - A vs. C: ED↓, FDS↓
  - A vs. D1: ED↓, FCR↓, FDS↓
  - A vs. D2: ED↓, FCR↓, FCU↓
  - A vs. D3: ECU↑, FCU↓, FDS↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real hammer hold determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E4- 2: Comparison of ICC between the criterion task and each simulation

	A-C	A-D1	A-D2	A-D3
Perceived effort	0.40	0.87	0.90	0.10
Grip force matching	0.85	0.32	0.58	-0.06
Average EMG	0.15	0.34	0.21	0.14

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture and grasp type
- Different sized handle
- Different shaped handle
- Different material surface
- Posture compared with force control

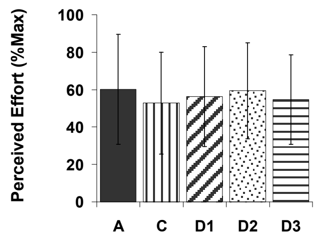


Figure E4-6: Perceived effort

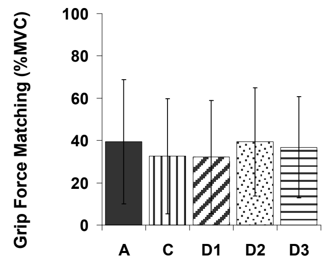


Figure E4-7: Grip strength matching

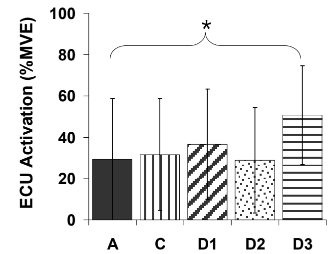


Figure E4-8: ECU %MVE

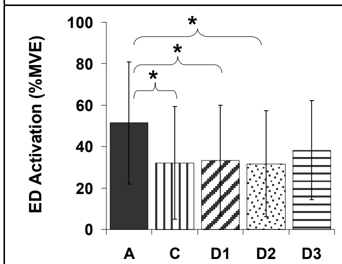


Figure E4-9: ED %MVE

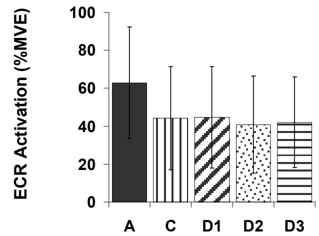


Figure E4-10: ECR %MVE

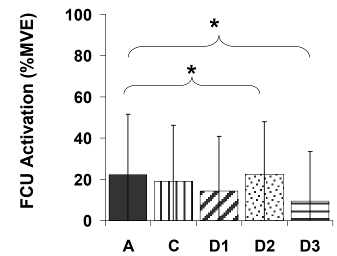


Figure E4-11: FCU %MVE

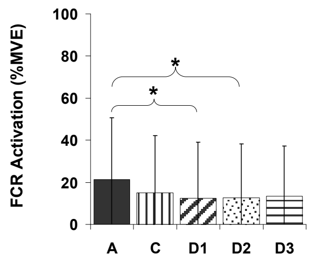


Figure E4-12: FCR %MVE

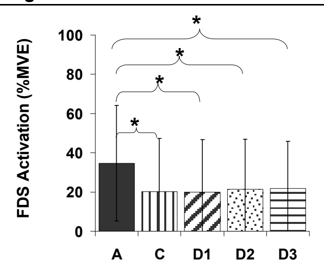


Figure E4-13: FDS %MVE

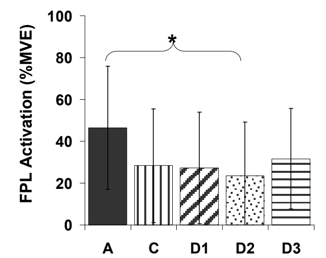


Figure E4-14: FPL %MVE

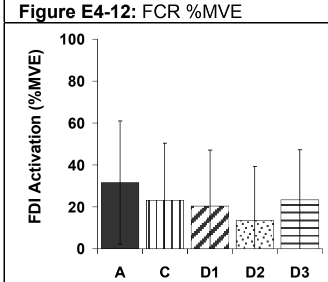


Figure E4-15: FDI %MVE

Table E4-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	C □		D1 △		D2 ○		D3 +	
Perceived Effort	N	36%	Y	27%	Y	36%	N	18%
Grip	N	27%	N	27%	Y	9%	Y	27%
ECU	Y	36%	N	9%	Y	18%	N	9%
ED	N	27%	N	0%	N	9%	N	18%
ECR	N	27%	N	27%	N	27%	N	27%
FCU	Y	73%	N	73%	Y	64%	N	73%
FCR	N	82%	N	100%	N	73%	N	64%
FDS	N	64%	N	55%	N	55%	N	64%
FPL	N	18%	N	18%	N	9%	N	18%
FDI	N	9%	Y	36%	N	27%	N	9%
Avg EMG		42%		40%		35%		35%

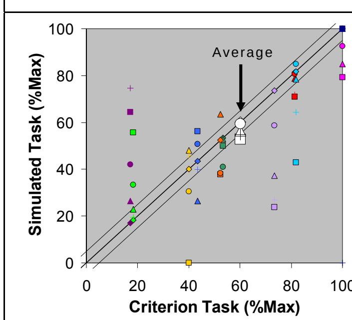


Figure E4-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

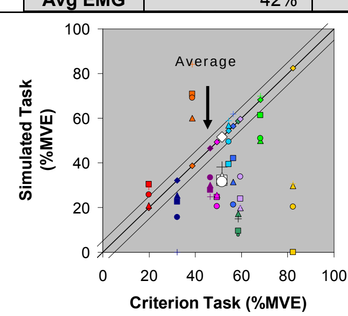


Figure E4-17: Comparison of task simulations within a ±5% range of criterion task for ED

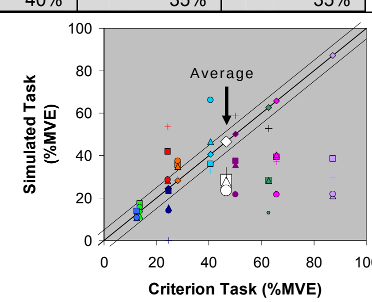


Figure E4-18: Comparison of task simulations within a ±5% range of criterion task for FPL

5. Radiator Hose Insertion Summary

- Apply upward force of 3.43N
- Apply push force of 13.5N using a volar grip

Figure E5-1: Criterion task: Push radiator hose onto real radiator

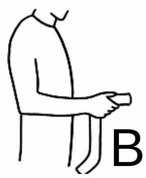


Figure E5-2: Real parts with simple feedback: Radiator hose attachment simulated with a constant force

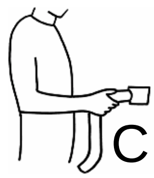


Figure E5-3: Real parts with force and moment feedback: Radiator hose attachment simulated with a hose attached a to force transducer

Figure E5-4: Simplified parts with force and moment feedback: Radiator hose attachment simulated with a horizontal 35mm handle fixed to a force transducer

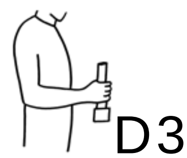


Figure E5-5: Simplified parts with force and moment feedback: Radiator hose attachment simulated with a vertical 35mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces required to insert this radiator hose (Table E5-1).
- **Posture:** The simulation with the radiator hose fixed to a force transducer (C) had a wrist posture with significantly more ulnar deviation than the most realistic task (A). The simulation with the horizontal handle (D2) had significantly more ulnar deviation and more extension than the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort between the real hose insertion and the simulations were found (Figure E5-6).
- **Grip Force Matching:** No significant differences in grip force matching between the real hose insertion and the simulations were found (Figure E5-7).

Table E5-1: Applied forces and moments

Task	Push Force (N)	Upward Force (N)
A*	13	3.43
B	13	3.43
C	12.8 ± 1.32	4.85 ± 1.25
D2	12.5 ± 1.22	5.06 ± 1.46
D3	12.6 ± 1.15	4.81 ± 0.85

* This task is a real hose insertion used to calculate forces. Participants were required to match these values within +/-10%.

- **Muscle Activation:** Significant differences between holding a real hammer (A) and simulating a hammer hold were found with the following simulations (Figures E5-8 to E5-15):
    - A vs. B: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓
    - A vs. C: ECU↓, FCU↓, FCR↓, FPL↓
    - A vs. D2: ECU↓, FCR↓
    - A vs. D3: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓, FDI↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real hammer hold determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E5-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D2	A-D3

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Changing degrees of freedom
- Different wrist posture and grip
- Different sized handle
- Different shaped handle
- Different material surface
- Obstructions

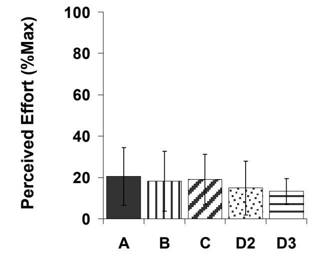


Figure E5-6: Perceived effort

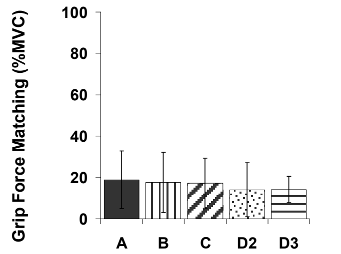


Figure E5-7: Grip strength matching

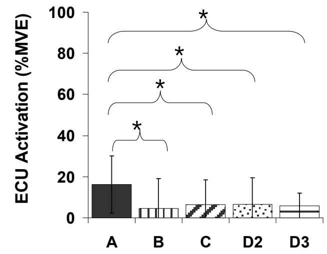


Figure E5-8: ECU %MVE

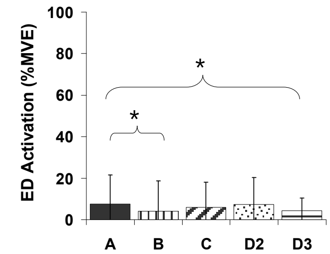


Figure E5-9: ED %MVE

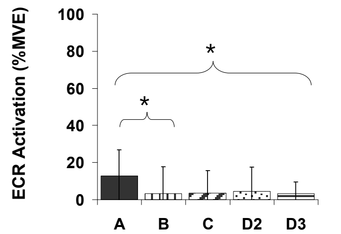


Figure E5-10: ECR %MVE

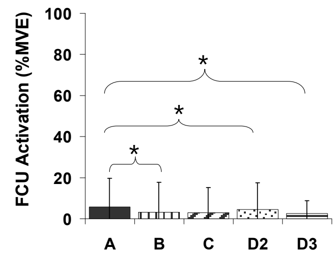


Figure E5-11: FCU %MVE

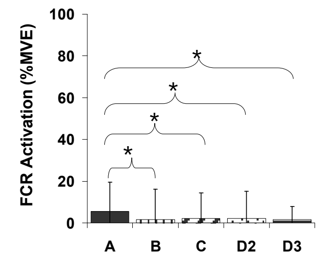


Figure E5-12: FCR %MVE

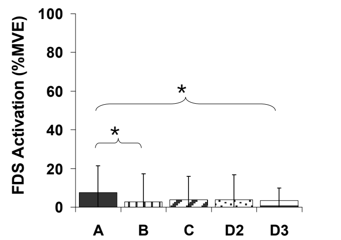


Figure E5-13: FDS %MVE

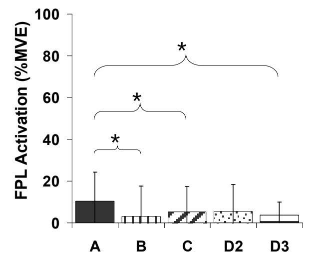


Figure E5-14: FPL %MVE

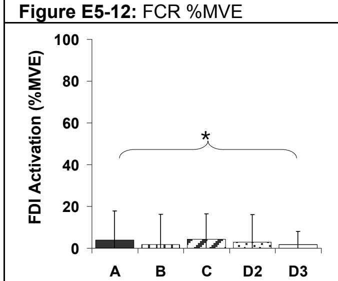


Figure E5-15: FDI %MVE

Table E5-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D2 ○		D3 +	
Perceived Effort	Y	27%	Y	45%	N	45%	N	45%
Grip	Y	27%	Y	27%	Y	36%	Y	18%
ECU	N	45%	N	36%	N	55%	N	45%
ED	Y	82%	Y	91%	Y	82%	Y	91%
ECR	N	73%	N	73%	N	64%	N	73%
FCU	Y	82%	Y	73%	Y	73%	Y	82%
FCR	Y	82%	Y	82%	Y	82%	Y	82%
FDS	Y	73%	Y	73%	Y	73%	Y	64%
FPL	N	73%	Y	64%	Y	64%	N	73%
FDI	Y	82%	N	9%	Y	100%	Y	82%
Avg EMG		74%		63%		74%		74%

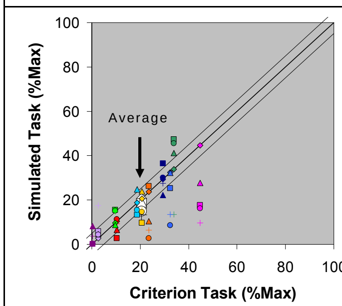


Figure E5-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

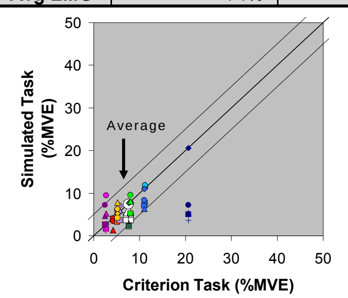


Figure E5-17: Comparison of task simulations within a ±5% range of criterion task for ED

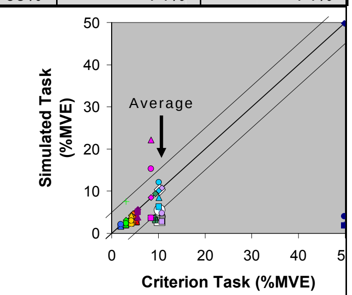


Figure E5-18: Comparison of task simulations within a ±5% range of criterion task for FPL

6. Window Seal Insertion Summary

- Apply dorsal force of 10N using a power grip
- Apply upward force of 26N

Figure E6-1:

Criterion task: Insert window seal into car door

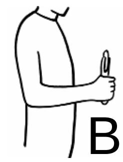


Figure E6-2:

Real parts with simple feedback: Push up and right against constant force

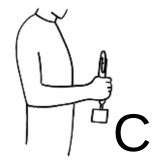


Figure E6-3:

Real parts with force and moment feedback: Window seal insertion with pizza wheel fixed to a force transducer

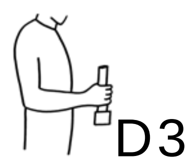


Figure E6-4:

Simplified parts with force and moment feedback: Window seal insertion simulated with a 25mm handle perpendicular to the axis of the forearm fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to insert a window seal (Table 1).
- **Posture:** No significant postural differences were noted.
- **Perceived Effort:** No significant differences in perceived effort between a real window seal insertion and the simulations were found (Figure E6-6).
- **Grip Force Matching:** Significantly lower estimated grip force was found between the real window seal insertion and the simulation with real parts (C) and simplified parts (D3) both with force and moment feedback (Figure E6-7).
- **Muscle Activation:** Significant differences between inserting a real window seal (A) and simulating that insertion by rotating and pushing against a constant force and moment found with the following simulations (Figures E6-8 to E6-15):
    - o A vs. B: FCU↓, FCR↓, FDS↓, FDI↓
    - o A vs. C: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓, FDI↓
    - o A vs. D3: ED↓, FCU↓, FDI↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real hammer hold determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table D-G 1: Applied forces

Task	Dorsal Force (N)	Upwards Force (N)
A*	10	26
B	10	26
C	7.9 ± 3.4	24.5 ± 8.0
D3	9.1 ± 2.2	28.4 ± 10.4

* This task is a real window seal insertion used to calculate forces and moments. Participants were required to match within +/-10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E6-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Different wrist/arm/shoulder posture
- Different sized handle
- Different shaped handle
- Different material surface
- Obstructions

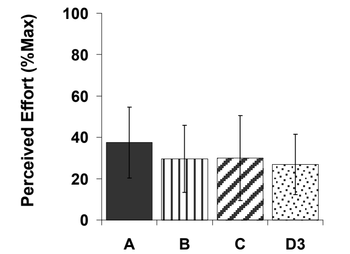


Figure E6-6: Perceived effort

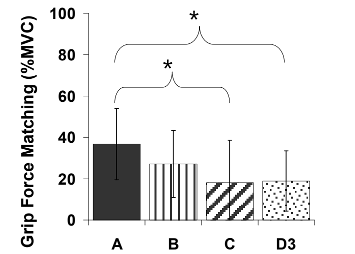


Figure E6-7: Grip strength matching

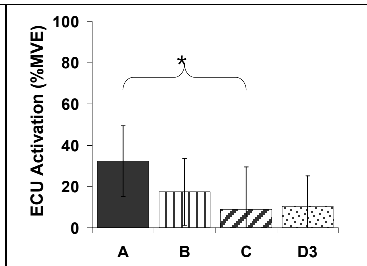


Figure E6-8: ECU %MVE

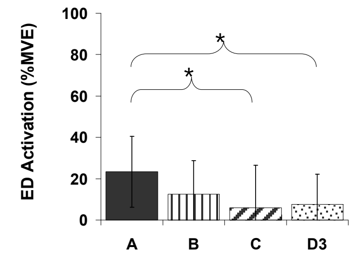


Figure E6-9: ED %MVE

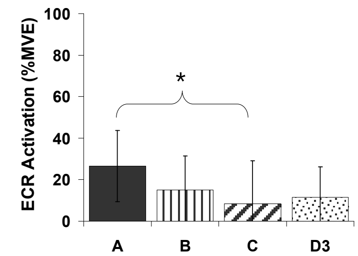


Figure E6-10: ECR %MVE

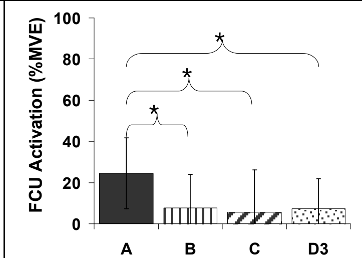


Figure E6-11: FCU %MVE

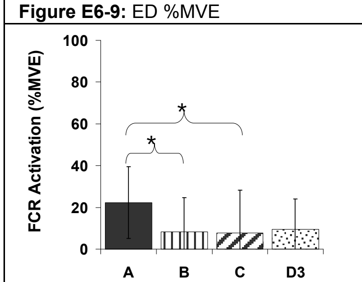


Figure E6-12: FCR %MVE

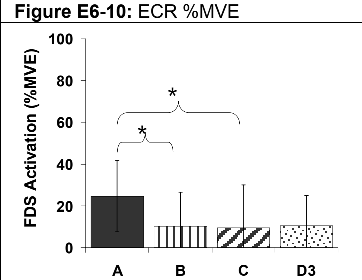


Figure E6-13: FDS %MVE

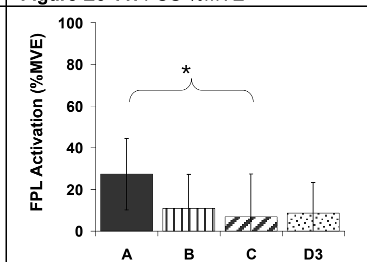


Figure E6-14: FPL %MVE

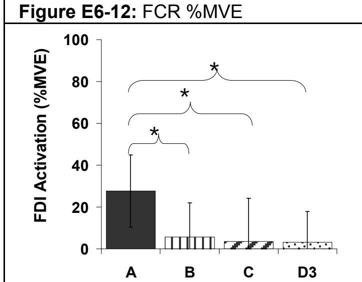


Figure E6-15: FDI %MVE

Table E6-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	N	0%	N	36%	N	18%
Grip	N	9%	N	18%	N	18%
ECU	N	18%	N	9%	N	9%
ED	N	36%	N	9%	N	0%
ECR	N	73%	N	36%	N	45%
FCU	N	9%	N	0%	N	0%
FCR	N	45%	N	45%	N	27%
FDS	N	45%	N	27%	N	18%
FPL	N	18%	N	18%	N	9%
FDI	N	27%	N	9%	N	27%
Avg EMG		34%		19%		17%

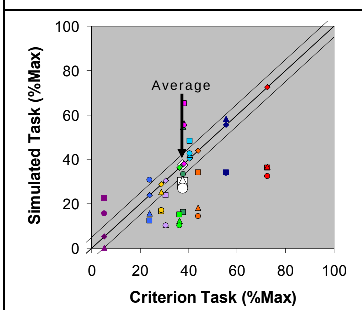


Figure E6-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

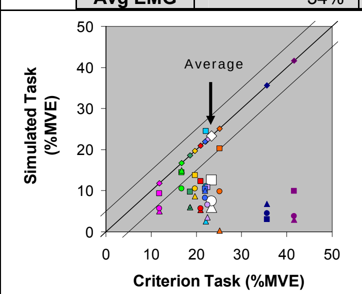


Figure E6-17: Comparison of task simulations within a ±5% range of criterion task for ED

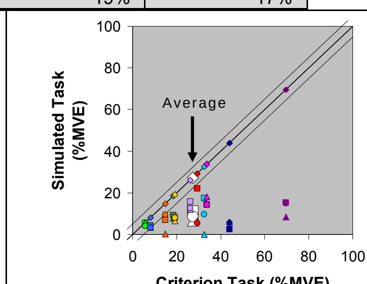


Figure E6-18: Comparison of task simulations within a ±5% r range of criterion task for FPL

7. Large Drill Hold Summary

- Apply upward force of 23N using a power grip

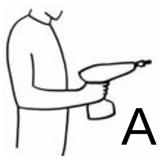


Figure E7-1:

Criterion task: Hold drill

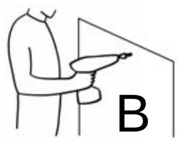


Figure E7-2:

Real parts with simple feedback: Hold drill while aiming at a specific target, no push force or torque is applied

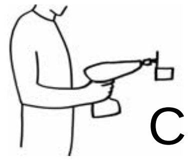


Figure E7-3:

Real parts with force and moment feedback: Simulated drill hold using a drill fixed to a force transducer

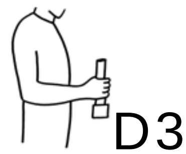


Figure E7-4:

Simplified parts with force and moment feedback: Simulate drill hold using with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table 1).
- **Posture:** No significant postural differences were noted.
- **Perceived Effort:** No significant differences in perceived effort between a real drill and the simulations were found (Figure E7-6).
- **Grip Force Matching:** No significant differences in grip force matching between a real drill hold and simulating that hold were found (Figure E7-7).
- **Muscle Activation:** No significant differences in muscle activation between holding a real drill (A) and each simulation were found (Figures E7-8 to E7-15).

Table E7-1: Applied force

Task	Upward Force (N)
A*	23
B	23
C	22.7 ± 4.0
D3	21.9 ± 5.0

* This task is a drill hammer hold used to calculate the force. Participants were required to match within +/- 10% of this value.

Intraclass Correlation Coefficients (ICC):

Table E7-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.49	0.80	0.76

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

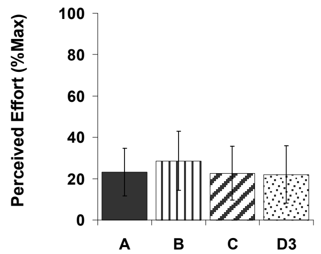


Figure E7-6: Perceived effort

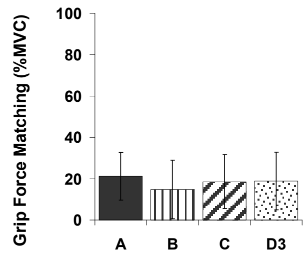


Figure E7-7: Grip strength matching

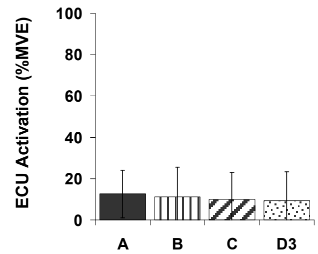


Figure E7-8: ECU %MVE

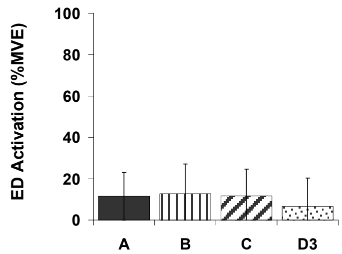


Figure E7-9: ED %MVE

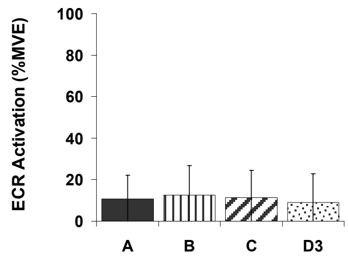


Figure E7-10: ECR %MVE

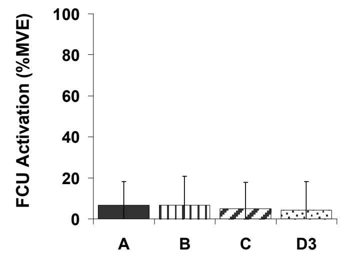


Figure E7-11: FCU %MVE

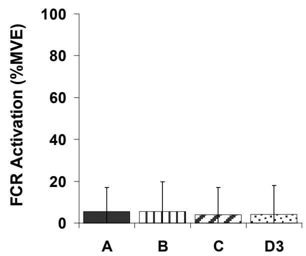


Figure E7-12: FCR %MVE

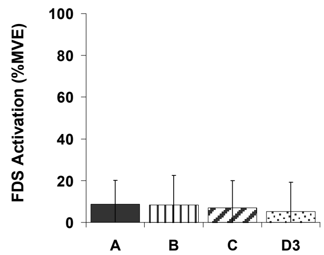


Figure E7-3: FDS %MVE

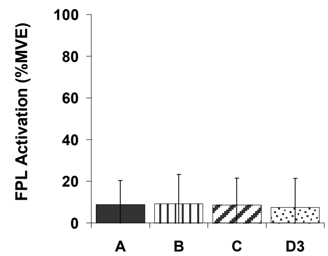


Figure E7-14: FPL %MVE

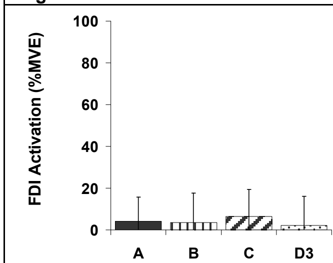


Figure E7-5: FDI %MVE

Table E7-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	N	18%	Y	55%	Y	64%
Grip	N	45%	Y	45%	Y	36%
ECU	Y	64%	Y	27%	Y	36%
ED	Y	82%	Y	36%	N	36%
ECR	Y	91%	Y	64%	Y	45%
FCU	Y	91%	Y	64%	Y	73%
FCR	Y	91%	Y	100%	Y	100%
FDS	Y	82%	Y	64%	Y	64%
FPL	Y	91%	Y	64%	Y	45%
FDI	Y	91%	N	9%	Y	55%
Avg EMG		85%		53%		57%

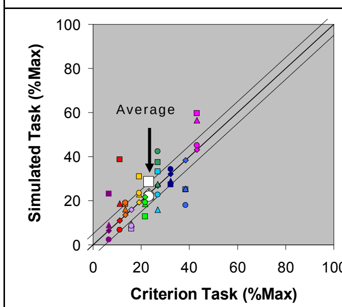


Figure E7-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

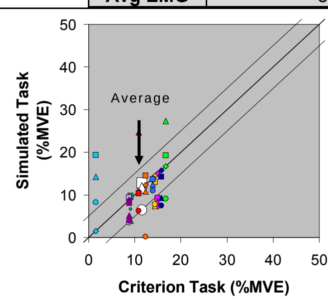


Figure E7-7: Comparison of task simulations within a ±5% range of criterion task for ED

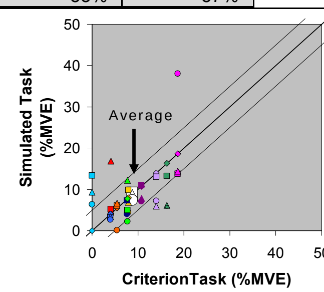


Figure E7-18: Comparison of task simulations within a ±5% range of criterion task for FPL

8. Large Drill Push Summary

- Apply upward force of 23N using a power grip
- Apply push force of 5N

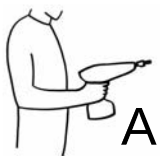


Figure E8-1:

Criterion task: Hold drill while pushing

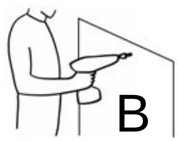


Figure E8- 2:

Real parts with simple feedback: Hold drill while aiming at a specific target and pushing

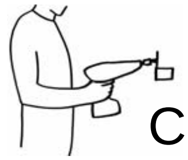


Figure E8- 3:

Real parts with force and moment feedback: Simulated drill push with drill fixed to a force transducer

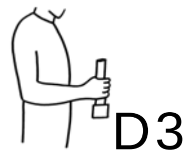


Figure E8-4:

Simplified parts with force and moment feedback: Simulated drill push with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table E8-1).
- **Posture:** No significant differences in posture between a real drill push and the simulations were found.
- **Perceived Effort:** No significant differences in perceived effort between a real drill push and the simulations were found (Figure E8-6).
- **Grip Force Matching:** No significant differences in grip force matching between a real drill push and simulating that push were found (Figure E8-7).

Table E8-1: Applied forces

Task	Upward Force (N)	Push Force (N)
A*	23	5
B	23	5
C	22.7 ± 3.2	5.5 ± 0.6
D3	21.9 ± 7.9	4.9 ± 2.1

* This task is a drill hold and push used to calculate the forces. Participants were required to match within +/-10% of these values.

- **Muscle Activation:** Significant differences in muscle activation between pushing with the real drill (A) and each simulation (Figures E8-8 to E8-15):
  - A vs. B:
  - A vs. C: ECU↓, ED↓, ECR↓
  - A vs. D: ECU↓, ED↓, ECR↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E8-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.32	0.48	0.61
Grip force matching	0.71	0.74	0.81

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

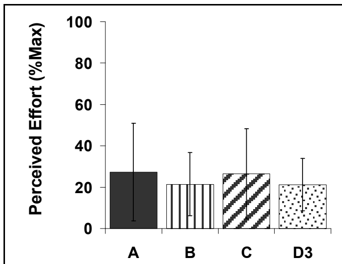


Figure E8-6: Perceived effort

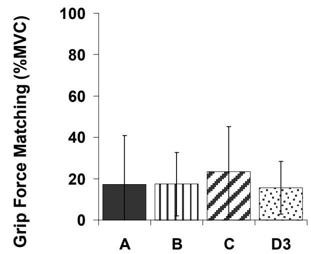


Figure E8-7: Grip strength matching

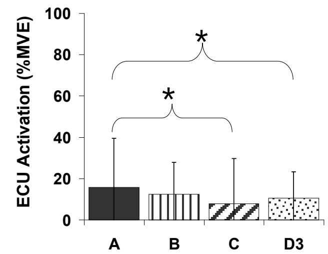


Figure E8-8: ECU %MVE

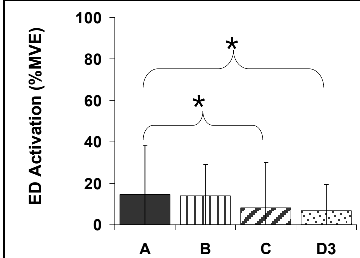


Figure E8-9: ED %MVE

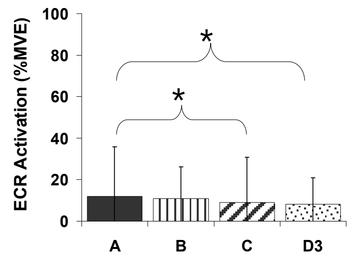


Figure E8-10: ECR %MVE

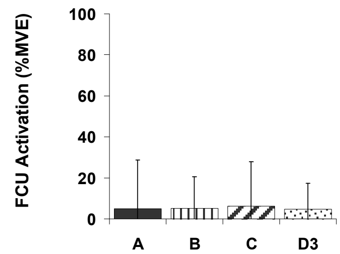


Figure E8-11: FCU %MVE

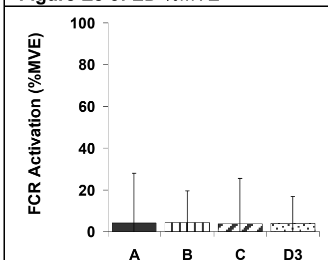


Figure E8-12: FCR %MVE

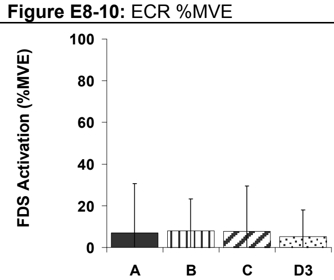


Figure E8-13: FDS %MVE

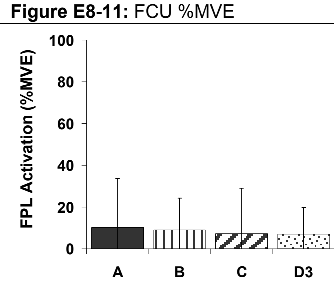


Figure E8-14: FPL %MVE

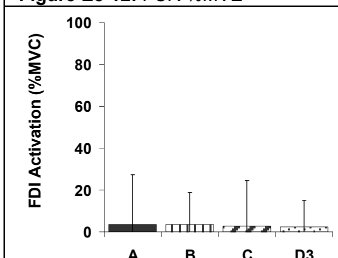


Figure E8-15: FDI %MVE

Table D-I 3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	N	27%	Y	36%	N	27%
Grip	Y	27%	N	27%	Y	45%
ECU	Y	64%	N	27%	N	36%
ED	Y	82%	N	73%	N	45%
ECR	Y	100%	Y	82%	Y	82%
FCU	Y	91%	Y	91%	Y	100%
FCR	Y	100%	Y	91%	Y	91%
FDS	Y	91%	Y	82%	Y	91%
FPL	Y	91%	Y	55%	Y	55%
FDI	Y	100%	N	0%	Y	91%
Avg EMG		90%		63%		74%

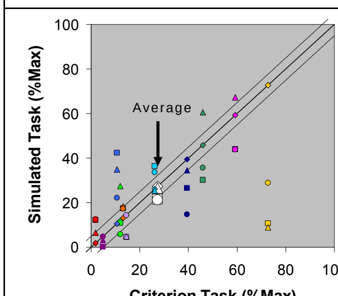


Figure E8-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

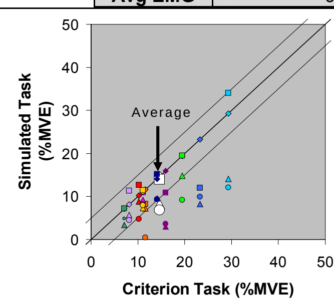


Figure E8-17: Comparison of task simulations within a ±5% range of criterion task for ED

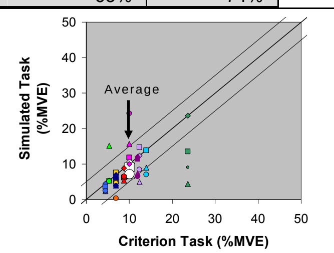


Figure E8-18: Comparison of task simulations within a ±5% range of criterion task for FPL

9. Large Drill Push & Torque Summary

- Apply upward force of 23N using a power grip
- Apply push force of 5N
- Apply pronator moment of 3Nm

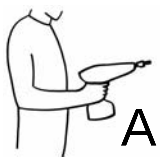


Figure E9-1:

Criterion task: Push and torque drill

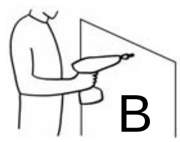


Figure E9-2:

Real parts with simple feedback: Push and torque drill while aiming at a specific target

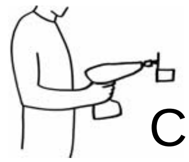


Figure E9-3:

Real parts with force and moment feedback: Simulated drill push and torque with drill fixed to a force transducer

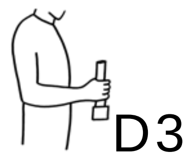


Figure E9- 4:

Simplified parts with force and moment feedback: Simulate drill push and torque using with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table E9-1).
- **Posture:** The simulation with real parts (C) and simplified parts (D3) both with force and moment feedback had wrist postures with significantly more ulnar deviation than the most realistic task (A).
- **Perceived Effort:** No significant differences in perceived effort between real drill use and the simulations were found (Figure E9-6).
- **Grip Force Matching:** No significant differences in grip force matching between real drill use and simulating that use were found (Figure E9-7).
- **Muscle Activation:** Significant differences in muscle activation between pushing & turning with the real drill (A) and each simulation (Figures E9-8 to E9-15):
    - o A vs. B:
    - o A vs. C: ECU↑
    - o A vs. D3:
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E9-1: Applied forces and moment

Task	Upward Force (N)	Push Force (N)	Pronator Moment (Nm)
A*	23	5	3
B	23	5	3
C	25.7 ± 3.2	5.8 ± 0.6	3.3 ± 0.6
D3	23.3 ± 7.9	5.4 ± 2.1	2.8 ± 0.6

* This task is a real drill push and turn used to calculate the forces. Participants were required to match within +/-10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E9-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.58	0.34	0.49

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Vibration for most realistic task but not all simulations

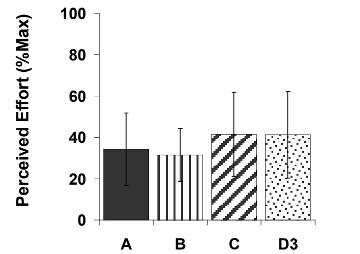


Figure E9-6 Perceived effort

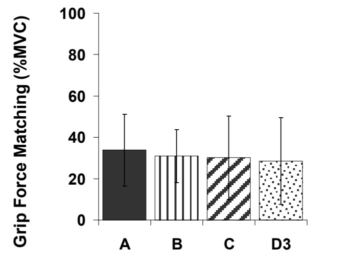


Figure E9-7: Grip strength matching

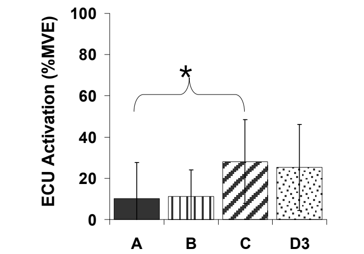


Figure E9-8: ECU %MVE

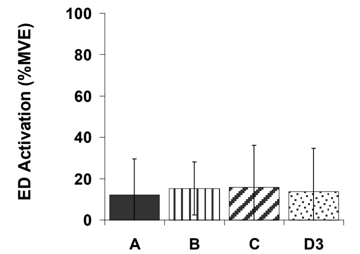


Figure E9-9: ED %MVE

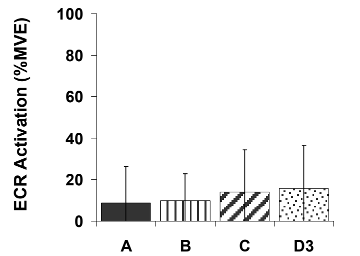


Figure E9-10: ECR %MVE

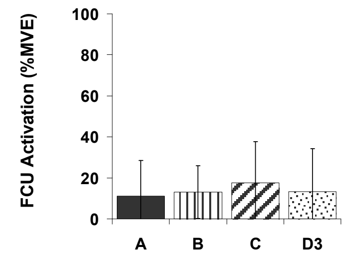


Figure E9-11: FCU %MVE

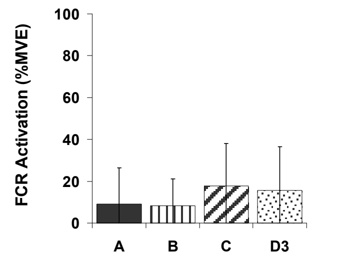


Figure E9-12: FCR %MVE

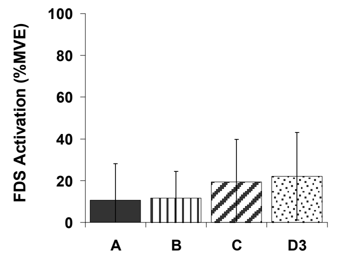


Figure E9-13: FDS %MVE

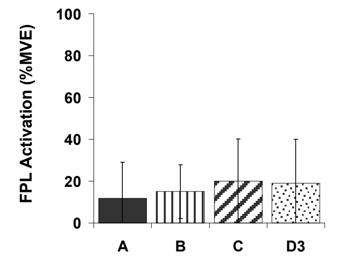


Figure E9-14: FPL %MVE

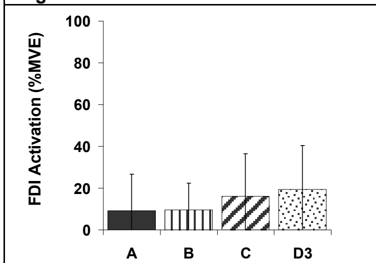


Figure E9-15: FDI %MVE

Table E9-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	Y	18%	N	18%	N	9%
Grip	Y	9%	Y	9%	N	27%
ECU	Y	64%	N	9%	N	18%
ED	Y	73%	Y	45%	Y	55%
ECR	Y	73%	N	64%	N	55%
FCU	Y	55%	N	45%	Y	45%
FCR	Y	73%	N	18%	N	45%
FDS	Y	91%	N	27%	N	27%
FPL	Y	45%	N	36%	N	27%
FDI	Y	82%	Y	18%	N	36%
Avg EMG		69%		33%		39%

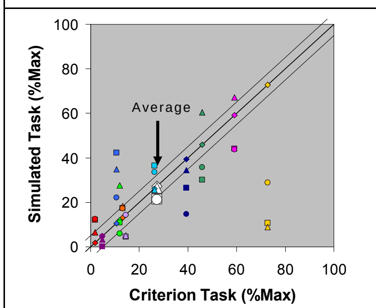


Figure E9-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

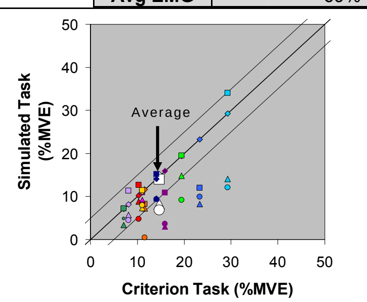


Figure E9-17: Comparison of task simulations within a ±5% range of criterion task for ED

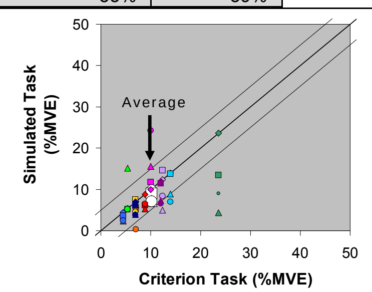


Figure E9-18: Comparison of task simulations within a ±5% range of criterion task for FPL

# 10. Small Drill Hold Summary	• Apply upward force of 7.4N using a power grip

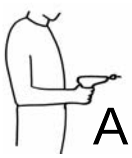


Figure E10-1:

Criterion task: Hold drill

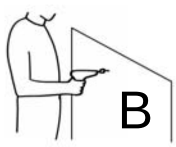


Figure E10-2:

Real parts with simple feedback: Hold drill while aiming at a specific target, no push force or torque is applied

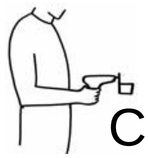


Figure E10-3:

Real parts with force and moment feedback: Simulated drill hold using a drill fixed to a force transducer

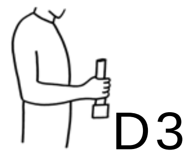


Figure E10-4:

Simplified parts with force and moment feedback: Simulate drill hold using a 25mm fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table E10-1).
- **Posture:** No significant postural differences were noted.
- **Perceived Effort:** No significant differences in perceived effort between a real drill hold and the simulations were found (Figure E10-6).
- **Grip Force Matching:** No significant differences in grip force matching were found between holding a real drill and the simulations (Figure E10-7).
- **Muscle Activation:** No significant differences in muscle activation between holding the real drill (A) and each simulation were found (Figures E10-8 to E10-15).
    - A vs. B:
    - A vs. C:
    - A vs. D3:
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E10-1: Applied force

Task	Upward Force (N)
A*	7.4
B	7.4
C	9.2 ± 2.8
D3	8.4 ± 2.0

* This task is a real drill hold used to calculate the force. Participants were required to match within +/-10% of this value.

Intraclass Correlation Coefficients (ICC):

Table E10-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.76	0.17	0.72
Grip force matching	0.74	0.55	0.42

Possible sources of these differences:

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

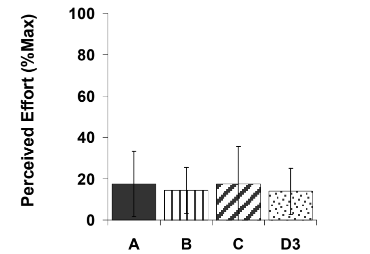


Figure E10-6: Perceived effort

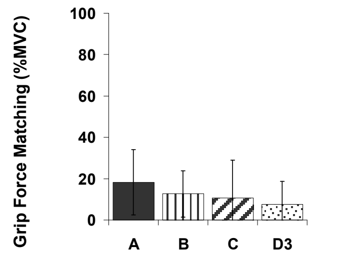


Figure E10-7: Grip strength matching

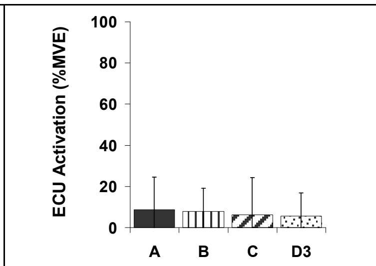


Figure E10-8: ECU %MVE

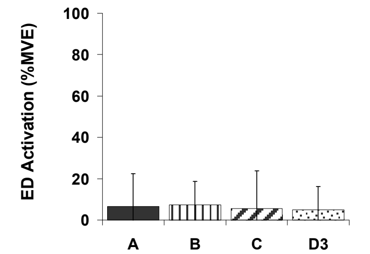


Figure E10-9: ED %MVE

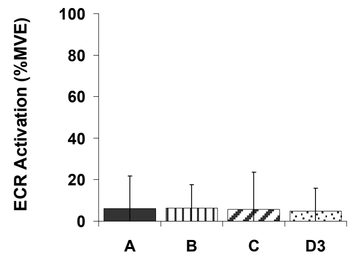


Figure E10-10: ECR %MVE

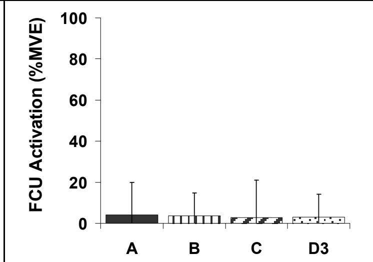


Figure E10-11: FCU %MVE

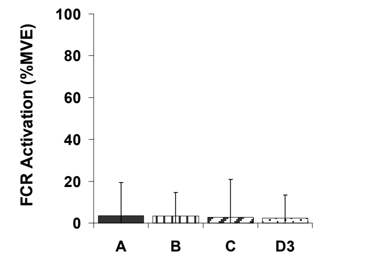


Figure E10-12: FCR %MVE

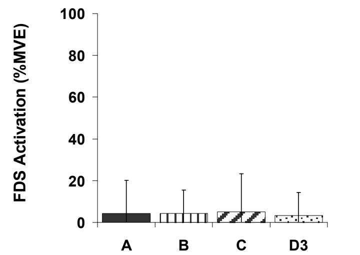


Figure E10-13: FDS %MVE

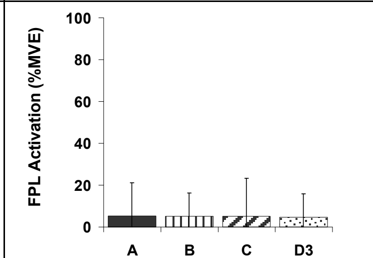


Figure E10-14: FPL %MVE

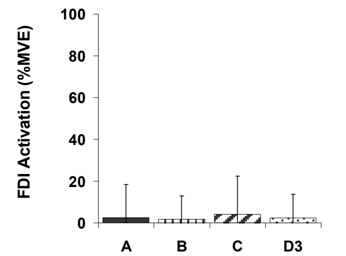


Figure E10-15: FDI %MVE

Table E10-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	Y	36%	Y	18%	Y	18%
Grip	N	64%	N	36%	N	64%
ECU	Y	73%	Y	36%	Y	55%
ED	Y	91%	Y	64%	Y	91%
ECR	Y	100%	Y	91%	Y	100%
FCU	Y	91%	Y	73%	Y	73%
FCR	Y	82%	Y	73%	Y	91%
FDS	Y	91%	Y	82%	Y	100%
FPL	Y	100%	Y	82%	Y	91%
FDI	Y	100%	N	0%	Y	82%
Avg EMG		91%		63%		85%

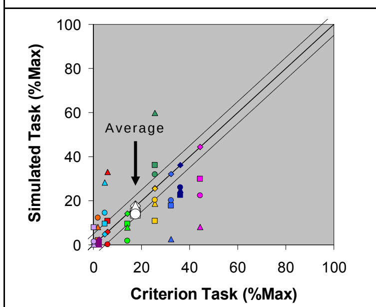


Figure E10-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

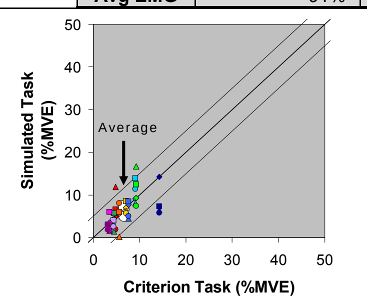


Figure E10-17: Comparison of task simulations within a ±5% range of criterion task for ED

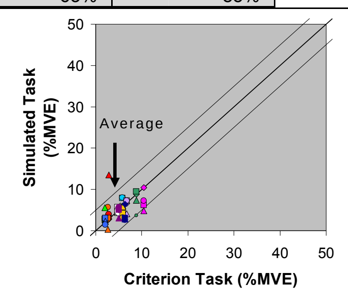


Figure E10-18: Comparison of task simulations within a ±5% range of criterion task for FPL

11. Small Drill Push Summary

- Apply upward force of 7.4N using a power grip
- Apply push force of 5N

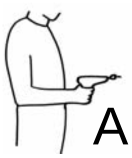


Figure E11-1:

Criterion task: Push drill

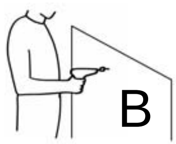


Figure E11-2:

Real parts with simple feedback: Push drill while aiming at a specific target, no torque is applied

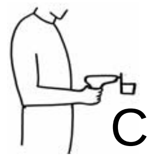


Figure E11-3:

Real parts with force and moment feedback: Simulated drill push with drill fixed to a force transducer

Figure E11-4:

Simplified parts with force and moment feedback: Simulate drill push with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table E11-1).
- **Posture:** No significant postural differences were noted.
- **Perceived Effort:** Significant differences in perceived effort between a real drill push (A) and the simulation with the drill fixed to a force transducer (C) were found (Figure E11-6).
- **Grip Force Matching:** Significant differences in grip force matching between a real drill push and the simulation with the drill fixed to a force transducer (C) and the vertical handle (D3) were noted (Figure E11-7).
- **Muscle Activation:** No significant differences in muscle activation between holding the real drill (A) and each simulation were found (Figures E11-8 to E11-15).
    - o A vs. B:
    - o A vs. C:
    - o A vs. D3:

Table E11-1: Applied forces

Task	Upward Force (N)	Push Force (N)
A*	7.4	5
B	7.4	5
C	9.5 ± 0.7	5.2 ± 3.8
D3	9.4 ± 0.9	4.9 ± 1.2

* This task is a real drill hold with a push used to calculate the forces. Participants were required to match within +/- 10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E11-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.50	0.71	0.70

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

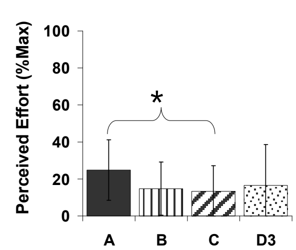


Figure E11-6: Perceived effort

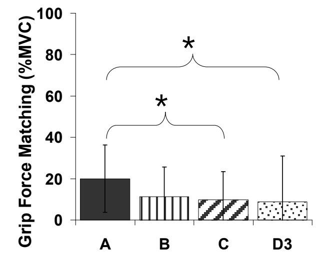


Figure E11-7: Grip strength matching

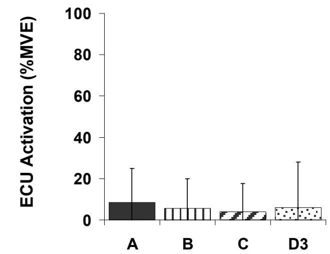


Figure E11-8: ECU %MVE

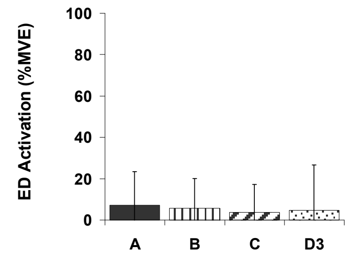


Figure E11-9: ED %MVE

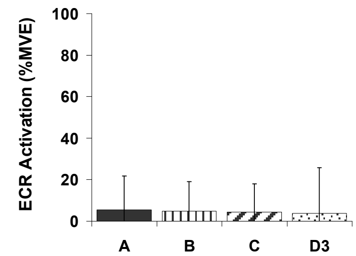


Figure E11-10: ECR %MVE

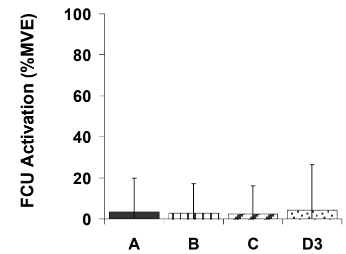


Figure E11-11: FCU %MVE

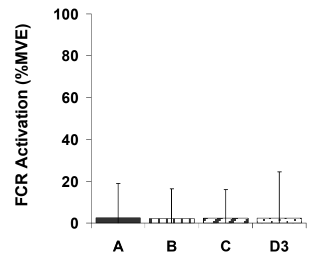


Figure E11-12: FCR %MVE

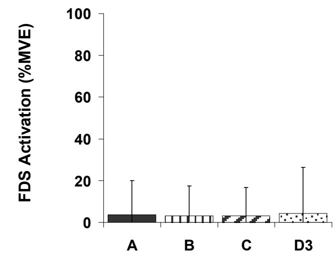


Figure E11-13: FDS %MVE

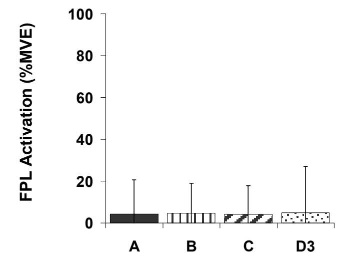


Figure E11-14: FPL %MVE

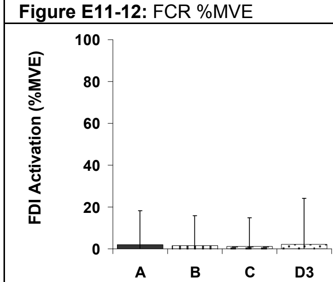


Figure E11-15: FDI %MVE

Table E11-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	N	27%	N	27%	N	27%
Grip	N	18%	N	45%	N	36%
ECU	Y	64%	Y	73%	Y	73%
ED	Y	82%	Y	73%	Y	91%
ECR	Y	91%	Y	91%	Y	82%
FCU	Y	100%	Y	100%	Y	91%
FCR	Y	100%	Y	100%	Y	100%
FDS	Y	100%	Y	100%	Y	91%
FPL	Y	91%	Y	91%	Y	91%
FDI	Y	100%	N	0%	Y	91%
Avg EMG		91%		78%		89%

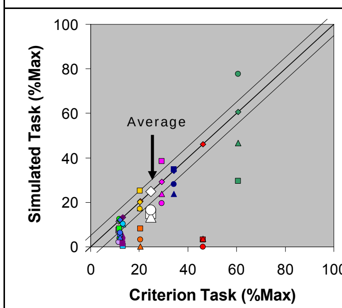


Figure E11-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

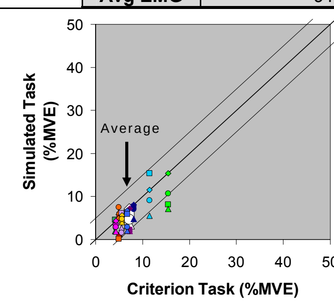


Figure E11-17: Comparison of task simulations within a ±5% range of criterion task for ED

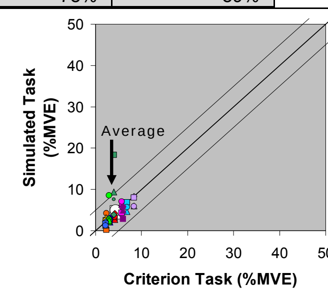


Figure E11-18: Comparison of task simulations within a ±5% range of criterion task for FPL

12. Small Drill Push & Torque Summary

- Apply upward force of 7.4N using a power grip
- Apply push force of 5N
- Apply pronator moment of 3Nm

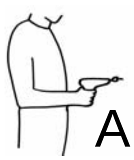


Figure E12-1:

Criterion task: Push and torque drill

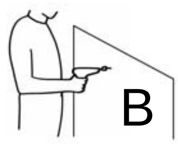


Figure E12-2:

Real parts with simplet feedback: Push and torque drill while aiming at a specific target, no push force or torque is applied

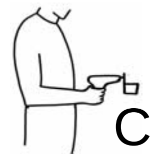


Figure E12-3:

Real parts with force and moment feedback: Simulated drill push and torque with a drill fixed to a force transducer

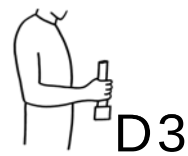


Figure E12-4:

Simplified parts with force and moment feedback: Simulate drill push and torque using a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to hold a drill (Table E12-1).
- **Posture:** The simulation with real parts and force and moment feedback (C) had significantly more pronation compared with the supinated position of the most realistic task (A). The simulation with the simplified parts and force and moment feedback (D3) had significantly more ulnar deviation compared to the radial deviation of the most realistic task (A).

Table E12-1: Applied forces and moment

Task	Upward Force (N)	Push Force (N)	Pronator Moment (Nm)
A*	7.4	5	3
B	7.4	5	3
C	10.0 ± 4.4	5.6 ± 1.8	2.9 ± 0.8
D3	7.1 ± 10.0	4.4 ± 1.2	2.5 ± 0.5

* This task is a real hammer hold with torque used to calculate the forces. Participants were required to match within +/-10% of these values.

- **Perceived Effort:** No significant differences in perceived effort between real drill use and the simulations were found (Figure E12-6).
- **Grip Force Matching:** Significant differences in grip force matching between the real drill (A) and the simulation with constant forces and moments (B) (Figure 7).
- **Muscle Activation:** Significant differences in muscle activation between holding the real drill (A) and each simulation were found (Figures E12-8 to E12-15).
    - A vs. B:
    - A vs. C: FCR↑, FDS↑, FPL↑
    - A vs. D3: FCR↑, FDS↑, FPL↑
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E12-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D3
Perceived effort	0.59	0.38	0.70

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Vibration for most realistic task but not all simulations

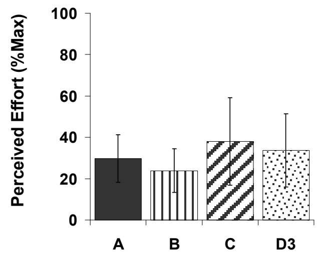


Figure E12-6: Perceived effort

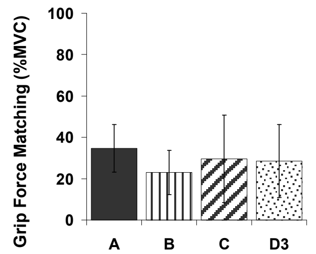


Figure E12-7: Grip strength matching

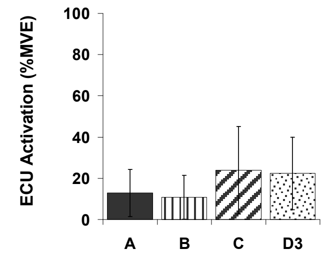


Figure E12-8: ECU %MVE

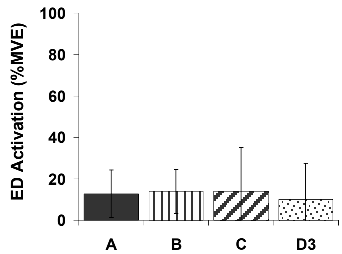


Figure E12-9: ED %MVE

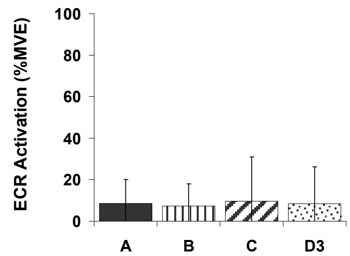


Figure E12-10: ECR %MVE

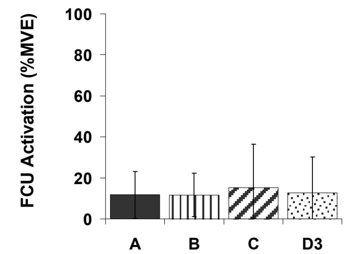


Figure E12-11: FCU %MVE

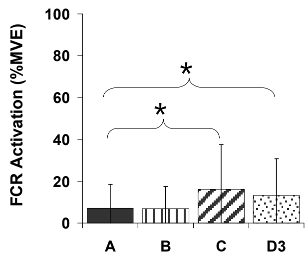


Figure E12-12: FCR %MVE

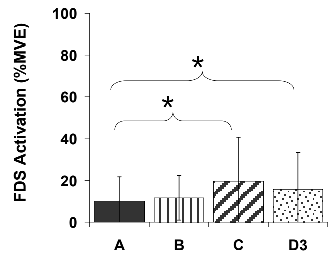


Figure E12-13: FDS %MVE

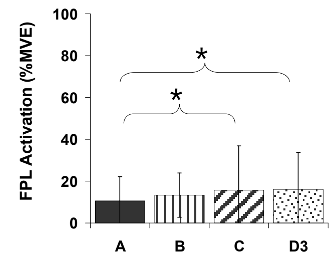


Figure E12-14: FPL %MVE

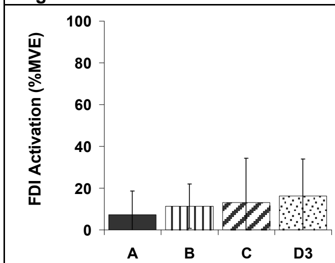


Figure E12-15: FDI %MVE

Table E12-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D3 ○	
Perceived Effort	N	18%	N	27%	Y	36%
Grip	N	9%	N	36%	N	36%
ECU	Y	55%	N	18%	N	36%
ED	Y	73%	Y	45%	Y	45%
ECR	Y	91%	Y	73%	Y	91%
FCU	Y	73%	Y	27%	Y	64%
FCR	Y	91%	N	18%	N	27%
FDS	Y	82%	N	36%	N	27%
FPL	Y	64%	N	55%	N	55%
FDI	Y	45%	N	18%	N	27%
Avg EMG		72%		36%		47%

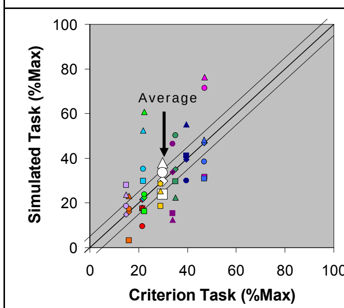


Figure E12-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

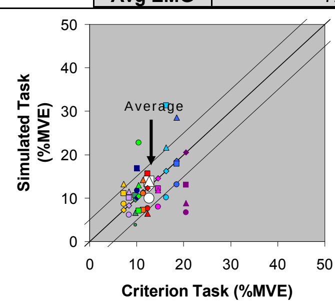


Figure E12-17: Comparison of task simulations within a ±5% range of criterion task for ED

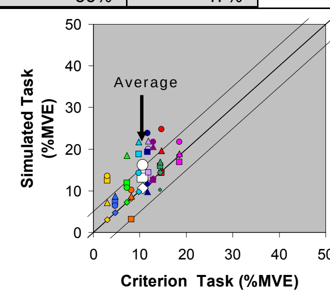


Figure E12-18: Comparison of task simulations within a ±5% range of criterion task for FPL

13. Wire harness (ORC1, wires)

- Apply push force of 15N using a modified lateral pinch (wires from connector are held within hand)

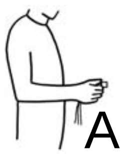


Figure E13-1:

Criterion task: Push to attach wire harness to connector

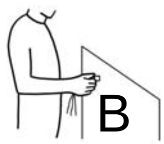


Figure E13- 2:

Real parts with simple feedback: Push wire harness against resistance

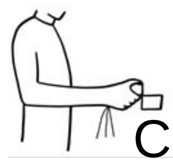


Figure E13- 3:

Real parts with force and moment feedback: Simulated wire harness push with a wire harness fixed to a force transducer

Figure E13- 4:

Simplified parts with force and moment feedback: Simulated wire harness push with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to attach an ORC connector (Table E13-1).
- **Posture:** The simulation with the horizontal pinch (D3) had a wrist position with significantly less ulnar deviation than the criterion task (A).
- **Perceived Effort:** No significant differences were found (Figure E13-6).
- **Grip Force Matching:** The estimated grip force required for for the most realistic task (A) was significantly greater then the simulation with the constant force (B) and the connector fixed to the force transducer (C) (Figure E13-7).
- **Muscle Activation:** Significant differences in muscle activation between attaching the real ORC connector (A) and each simulation were found (Figures 8-15).
    - A vs. B: FCU↓. FCR↓, FDS↓, FPL↓, FDI↓
    - A vs. C:
    - A vs. D3:
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E13-1: Applied force

Task	Push Force (N)
A*	15
B	15
C	13.1 ± 5.0
D4	11.7 ± 6.2

* This task is a real ORC connection used to calculate the force. Participants were required to match within +/-10% of this value.

Intraclass Correlation Coefficients (ICC):

Table E13-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D4
Perceived effort	0.24	0.26	0.37

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Changes in degrees of freedom
- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Hybrid grip for some simulations

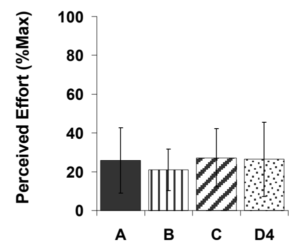


Figure E13-6: Perceived effort

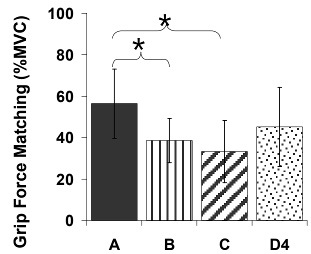


Figure E13-7: Grip strength matching

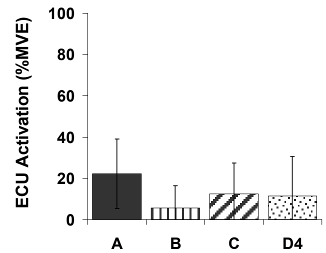


Figure E13-8: ECU %MVE

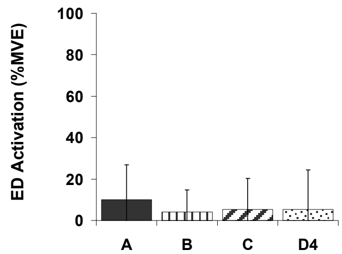


Figure E13-9: ED %MVE

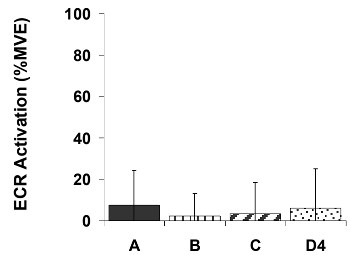


Figure E13-10: ECR %MVE

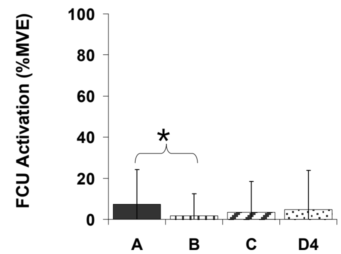


Figure E13-11: FCU %MVE

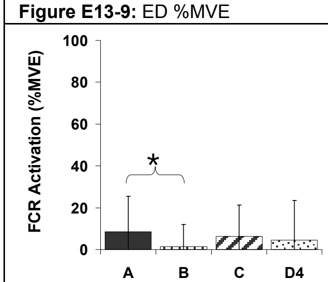


Figure E13-12: FCR %MVE

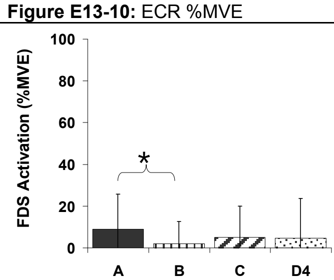


Figure E13-13: FDS %MVE

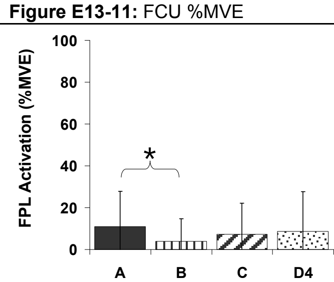


Figure E13-14: FPL %MVE

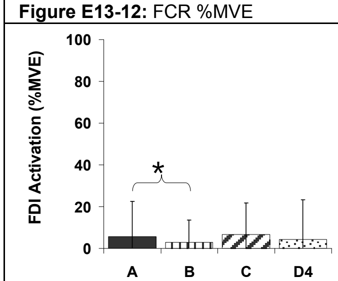


Figure E13-15: FDI %MVE

Table E13-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D4 ○	
Perceived Effort	Y	27%	Y	18%	Y	27%
Grip	N	36%	N	27%	N	0%
ECU	N	9%	N	27%	N	27%
ED	N	45%	Y	64%	Y	45%
ECR	N	82%	Y	73%	Y	64%
FCU	N	45%	Y	45%	Y	55%
FCR	N	55%	Y	45%	Y	73%
FDS	N	45%	Y	64%	Y	64%
FPL	N	55%	Y	73%	Y	45%
FDI	Y	73%	N	9%	N	73%
Avg EMG		51%		50%		56%

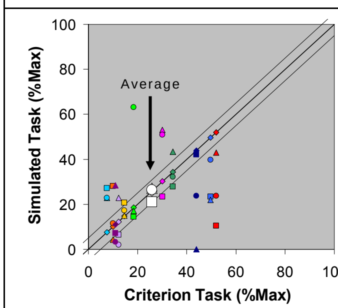


Figure E13-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

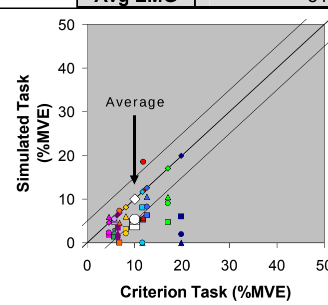


Figure E13-17: Comparison of task simulations within a ±5% range of criterion task for ED

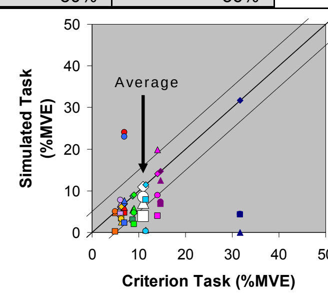


Figure E13-18: Comparison of task simulations within a ±5% range of criterion task for FPL

14. Wire harness (ORC2, no wires)

- Apply push force of 15N using a standard lateral pinch (modification removed by cutting wires)

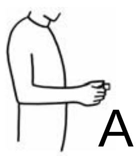


Figure E14-1:

Criterion task: Push to attach wire harness to connector (wires removed)

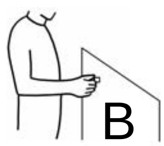


Figure E14-2:

Real parts with simple feedback: Push wire harness against resistance (wires removed)

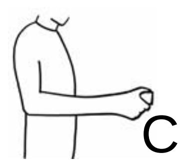


Figure E14-3:

Real parts with force and moment feedback: Simulated wire harness push with a wire harness fixed to a force transducer (wires removed)

Figure E14-4:

Simplified parts with force and moment feedback: Simulated wire harness push with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to attach an ORC connector (Table E14-1).
- **Posture:** No significant postural differences were noted.
- **Perceived Effort:** No significant differences in perceived were found (Figure E14-6).
- **Grip Force Matching:** The estimated grip force for the criterion task (A) was significantly greater than that of each of the simulations (B, C, D3) (Figure E14-7).
- **Muscle Activation:** The muscle activation of the criterion task (A) was greater than each of the simulations for the following muscles (Figures E14-8 to E14-15).
    - A vs. B: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓
    - A vs. C: ECU↓, ED↓, ECR↓, FCU↓, FCR↓
    - A vs. D3: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E14-1: Applied force

Task	Push Force (N)
A*	15
B	15
C	14.4 ± 1.1
D4	14.1 ± 0.7

* This task is a real ORC connection used to calculate the force. Participants were required to match within +/-10% of this value.

Intraclass Correlation Coefficients (ICC):

Table E14-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D4
Perceived effort	0.50	0.81	0.69
Grip force matching	0.24	0.80	0.74

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Changes in degrees of freedom
- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

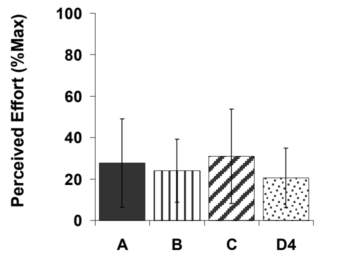


Figure E14-6: Perceived effort

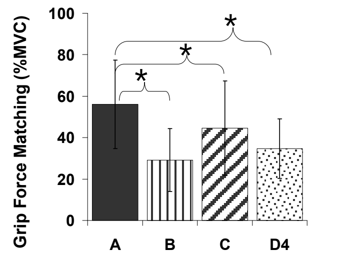


Figure E14-7: Grip strength matching

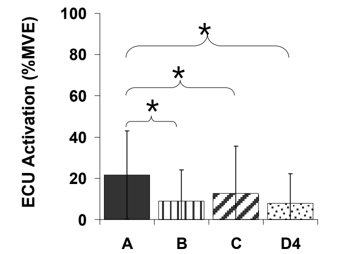


Figure E14-8: ECU %MVE

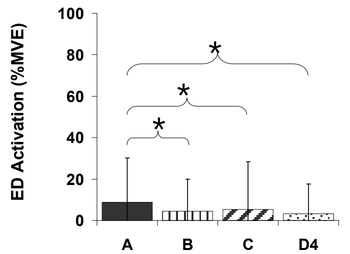


Figure E14-9: ED %MVE

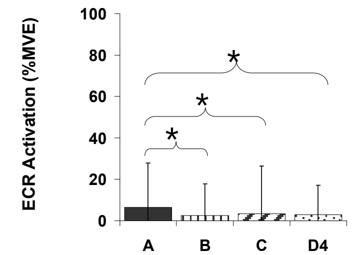


Figure E14-10: ECR %MVE

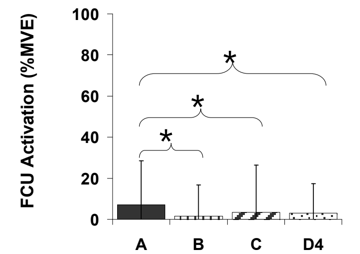


Figure E14-11: FCU %MVE

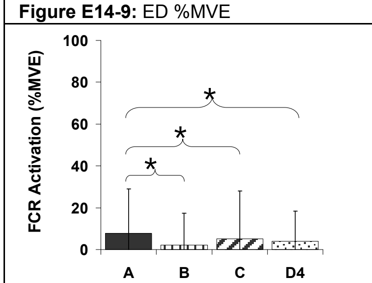


Figure E14-12: FCR %MVE

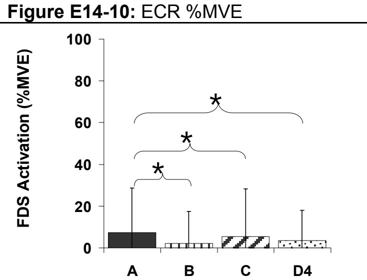


Figure E14-13: FDS %MVE

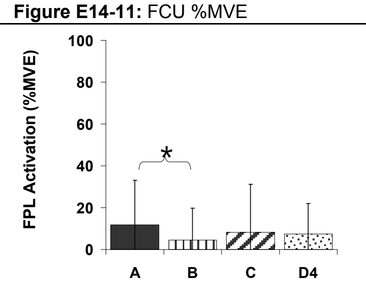


Figure E14-14: FPL %MVE

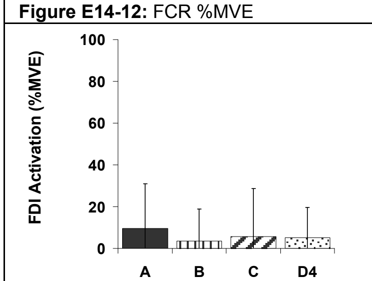


Figure E14-15: FDI %MVE

Table E14-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D4 ○	
Perceived Effort	Y	45%	Y	27%	Y	36%
Grip	N	18%	N	27%	N	9%
ECU	N	36%	N	9%	N	18%
ED	Y	64%	Y	0%	Y	9%
ECR	Y	82%	Y	27%	Y	27%
FCU	N	45%	Y	73%	Y	64%
FCR	N	45%	Y	100%	Y	73%
FDS	N	36%	Y	55%	Y	55%
FPL	N	27%	Y	18%	Y	9%
FDI	N	64%	N	36%	N	27%
Avg EMG		50%		40%		35%

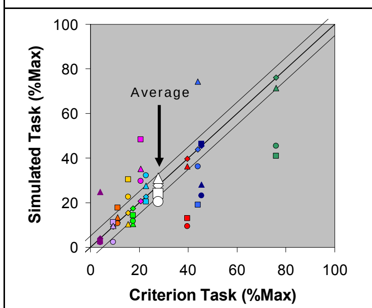


Figure E14-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

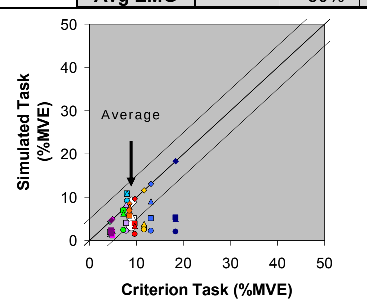


Figure E14-17: Comparison of task simulations within a ±5% range of criterion task for ED

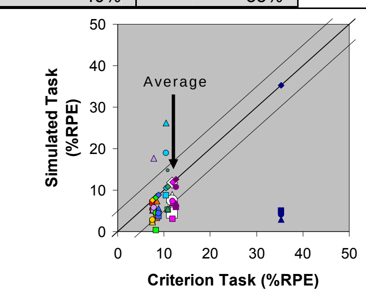


Figure E14-18: Comparison of task simulations within a ±5% range of criterion task for FPL

15. Plate Hold 0.5kg Summary	• Apply upwards force of 6.9N using a lateral pinch • Apply radial deviator moment of 0.6Nm

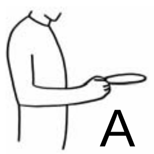


Figure E15-1:

Criterion task: Hold plate with 0.5kg

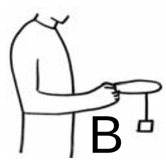


Figure E15- 2:

Real parts with simple feedback: Hold plate with constant hanging mass

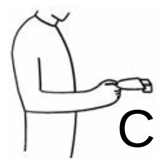


Figure E15- 3:

Real parts with force and moment feedback: Simulate plate hold with a plate fixed to a force transducer

Figure E15-4:

Simplified parts with force and moment feedback: Simulate plate hold with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to hold a plate (Table E15-1).
- **Posture:** The simulation with the horizontal pinch (D4) had a wrist position with significantly less ulnar deviation than the criterion task (A).
- **Perceived Effort:** The criterion task (A) had a significantly lower average perceived effort than the simulation with the vertical handle (D4) (Figure E15-6).
- **Grip Force Matching:** No significant differences in grip force matching between holding a real plate and simulating that hold were found (Figure E15-7).

Table E15-1: Applied force and moment

Task	Upwards Force (N)	Radial Deviator Moment (Nm)
A*	6.9	0.6
B	6.9	0.6
C	7.8 ± 1.23	0.06 ± 0.12
D4	6.8 ± 1.40	0.35 ± 0.17

* This task is a real plate hold used to calculate forces and moments. Participants were required to match within +/-10% of these values.

- **Muscle Activation:** Significantly higher muscle activation between holding a real plate (A) and the simulations listed below were found (Figures E15- 8 to E15-15).
  - A vs. B:
  - A vs. C:
  - A vs. D4: ED↑, FCU↑
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E15-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D4
Perceived effort	0.85	0.62	0.40

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture[1]
- Different sized handle[2]
- Different shaped handle[3]
- Different material surface[4]

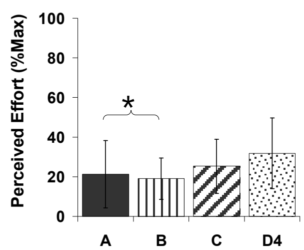


Figure E15-6: Perceived effort

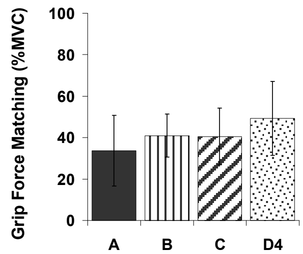


Figure E15-7: Grip strength matching

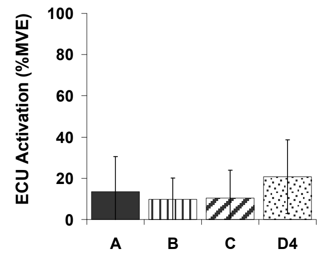


Figure E15-8: ECU %MVE

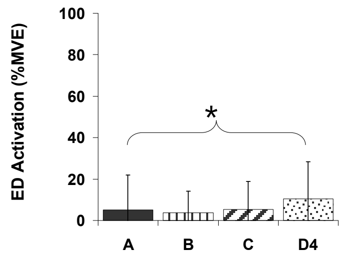


Figure E15-9: ED %MVE

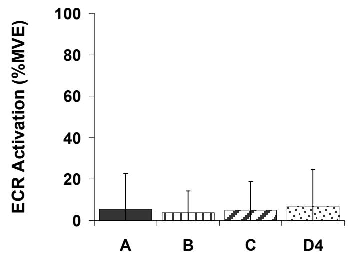


Figure E15-10: ECR %MVE

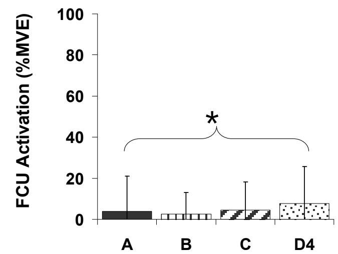


Figure E15-11: FCU %MVE

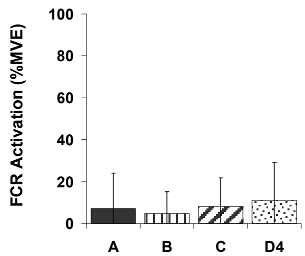


Figure E15-12: FCR %MVE

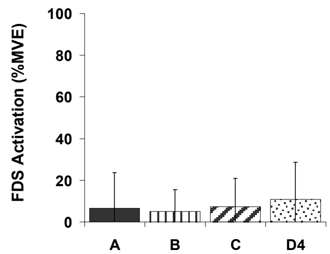


Figure E15-13: FDS %MVE

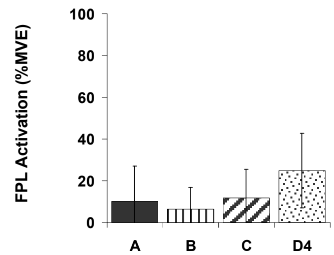


Figure E15-14: FPL %MVE

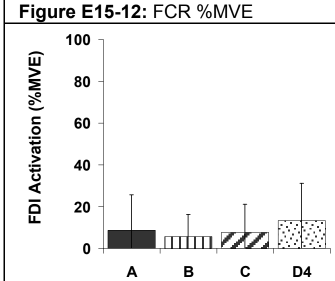


Figure E15-15: FDI %MVE

Table E15-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D4 ○	
Perceived Effort	Y	73%	Y	36%	N	45%
Grip	N	36%	N	9%	N	9%
ECU	Y	45%	Y	64%	N	27%
ED	Y	100%	Y	100%	N	55%
ECR	Y	91%	Y	100%	Y	91%
FCU	Y	91%	Y	100%	Y	73%
FCR	Y	91%	Y	82%	Y	73%
FDS	Y	91%	Y	82%	Y	64%
FPL	Y	73%	Y	82%	N	27%
FDI	Y	73%	N	18%	Y	27%
Avg EMG		82%		78%		55%

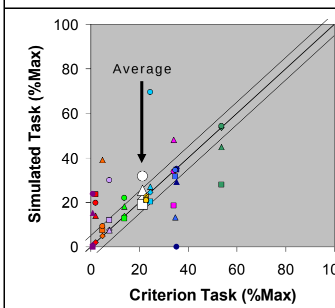


Figure E15-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

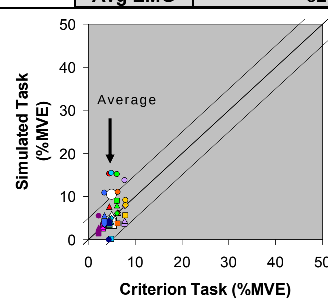


Figure E15-17: Comparison of task simulations within a ±5% range of criterion task for ED

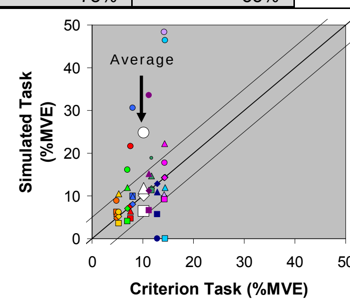


Figure E15-18: Comparison of task simulations within a ±5% range of criterion task for FPL

16. Plate Hold 2.2kg Summary

- Apply upwards force of 24N using a lateral pinch
- Apply radial deviator moment of 2Nm

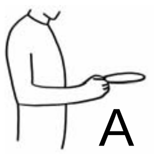


Figure E16-1:

Criterion task: Hold plate with 2.2kg

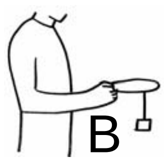


Figure E16-2:

Real parts with simple feedback: Hold plate with constant hanging mass

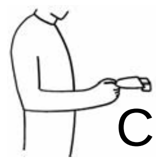


Figure E16-3:

Real parts with force and moment feedback: Simulate plate hold with a plate fixed to a force transducer

Figure E16-4:

Simplified parts with force and moment feedback: Simulate plate hold with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to hold a plate (Table E16-1).
- **Posture:** No significant differences in posture between holding a real plate (A) and the simulations were found.
- **Perceived Effort:** No significant differences in perceived effort between holding a real plate and the simulations were found (Figure E16-6).
- **Grip Force Matching:** No significant differences in grip force matching between holding a real plate and simulating that hold were found (Figure E16-7).

Table E16-1: Applied force and moment

Task	Upwards Force (N)	Radial Deviator Moment (Nm)
A*	24	2
B	24	2
C	26.6 ± 9.0	0.20 ± 1.21
D4	22.2 ± 5.6	1.12 ± 0.58

* This task is a real plate hold used to calculate forces and moments. Participants were required to match within +/-10% of these values.

- **Muscle Activation:** Significantly lower muscle activation between holding a real plate (A) and the simulations listed below were found (Figures E16-8 to E16-15).
  - o A vs. B:
  - o A vs. C:
  - o A vs. D4: FCU↑
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Intraclass Correlation Coefficients (ICC):

Table E16-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D4
Perceived effort	0.55	0.61	0.32

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture[1]
- Different sized handle[2]
- Different shaped handle[3]
- Different material surface[4]

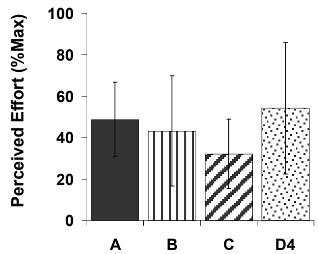


Figure E16-6: Perceived effort

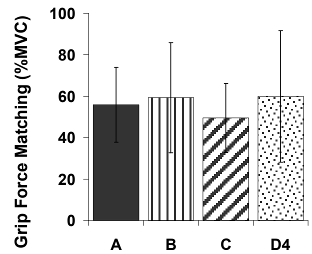


Figure E16-7: Grip strength matching

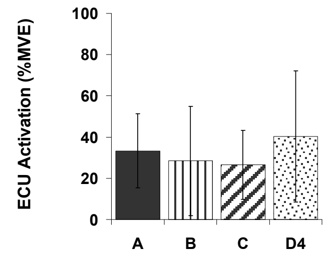


Figure E16-8: ECU %MVE

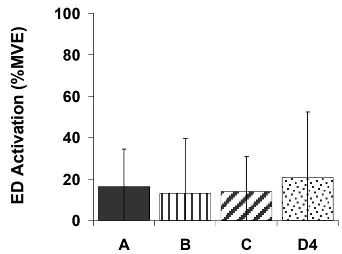


Figure E16-9: ED %MVE

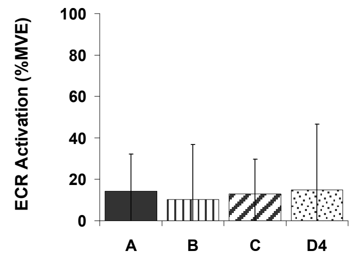


Figure E16-10: ECR %MVE

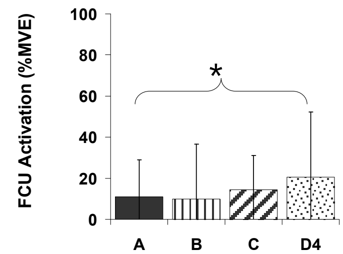


Figure E16-11: FCU %MVE

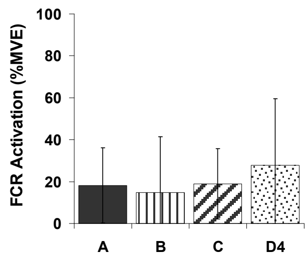


Figure E16-12: FCR %MVE

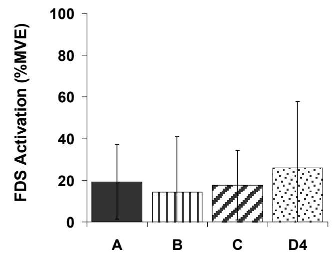


Figure E16-13: FDS %MVE

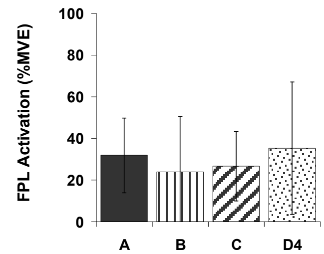


Figure E16-14: FPL %MVE

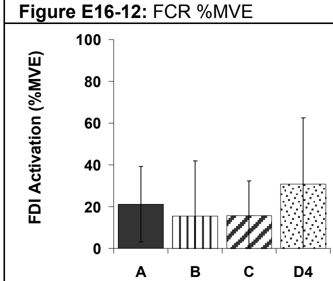


Figure E16-15: FDI %MVE

Table E16-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D4 ○	
Perceived Effort	N	0%	N	18%	N	9%
Grip	Y	27%	N	0%	Y	27%
ECU	Y	9%	N	27%	N	27%
ED	Y	36%	Y	36%	Y	45%
ECR	Y	55%	Y	55%	Y	73%
FCU	Y	64%	Y	55%	N	27%
FCR	Y	45%	Y	64%	N	36%
FDS	Y	36%	Y	73%	N	55%
FPL	N	27%	N	9%	Y	36%
FDI	N	45%	Y	9%	N	18%
Avg EMG		40%		41%		40%

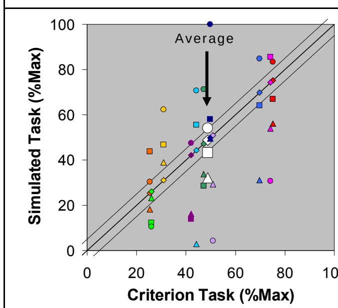


Figure E16-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

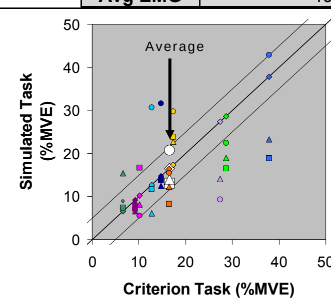


Figure E16-17: Comparison of task simulations within a ±5% range of criterion task for ED

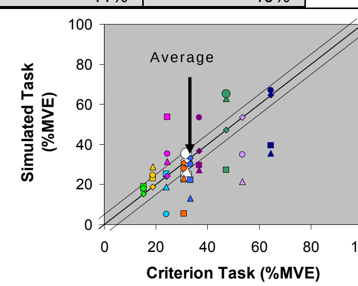


Figure E16-18: Comparison of task simulations within a ±5% range of criterion task for FPL

17. Fastener Init. Extended Summary	• Apply palmar force of 1.0N using a pulp pinch • Apply supinator moment of 0.03Nm

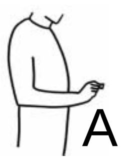


Figure E17-1:

Criterion task: Rotate nut on bolt

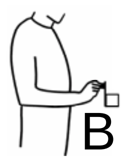


Figure E17-2:

Real parts with simple feedback: Rotate nut against constant force and moment

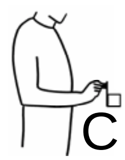


Figure E17-3:

Real parts with force and moment feedback: Nut rotation simulated with a nut fixed to a force transducer

Figure E17-4:

Simplified parts with force and moment feedback: Nut rotation simulated with a 25mm handle parallel to the axis of the forearm fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to turn a nut (Table E17-1).
- **Posture:** The simulation with the nut against a constant force (B) required a significantly more supinated posture than the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort were found (Figure E17-6).
- **Grip Force Matching:** No significant differences in grip force matching between were found (Figure E17-7).
- **Muscle Activation:** Significant differences in muscle activation between turning a real nut (A) and each simulation were found (Figures E17-8 to E17-15).
    - o A vs. B: ECU↓, ED↓, FCU↓, FCR↓, FDS↓, FPL↓
    - o A vs. C: ECR↓, FCR↓
    - o A vs. D6: FCU↓, FCR↓, FDS↓, FPL↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E17-1: Applied forces and moments

Task	Palmar Force (N)	Ulnar Moment (Nm)
A*	0.95	0.03
B	0.95	0.03
C	0.69 ± 0.51	0.119 ± 0.183
D6	1.13 ± 0.34	-0.050 ± 0.073

* This task is a real nut turn used to calculate forces and moments. Participants were required to match within +/-10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E17-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D6
Perceived effort	0.28	0.17	0.64

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Changes in degrees of freedom
- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

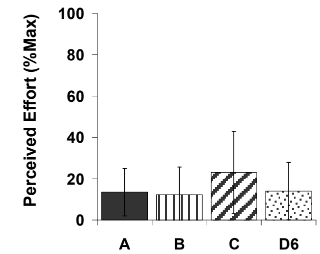


Figure E17-6: Perceived effort

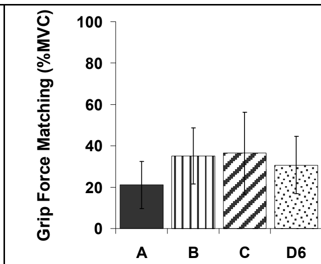


Figure E17-7: Grip strength matching

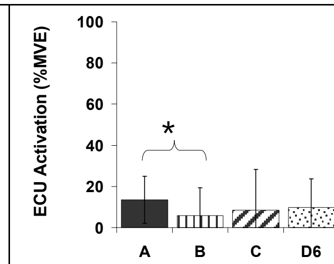


Figure E17-8: ECU %MVE

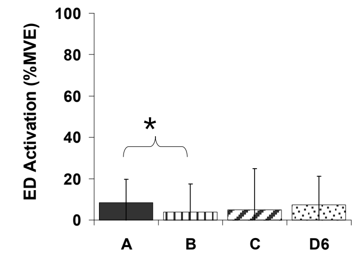


Figure E17-9: ED %MVE

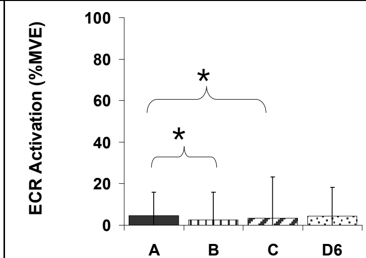


Figure E17-10: ECR %MVE

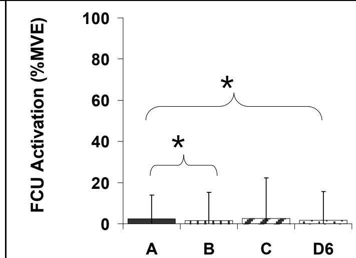


Figure E17-11: FCU %MVE

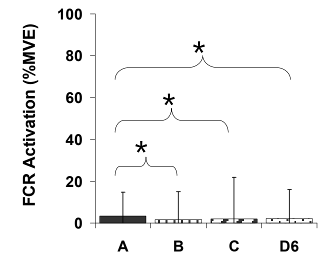


Figure E17-12: FCR %MVE

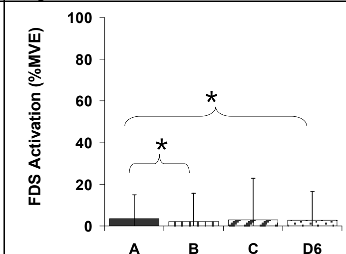


Figure E17-13: FDS %MVE

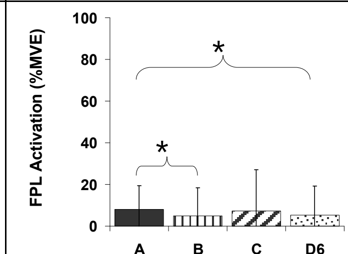


Figure E17-14: FPL %MVE

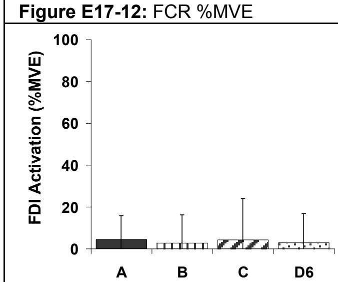


Figure E17-15: FDI %MVE

Table E17-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D6 ○	
Perceived Effort	Y	64%	N	27%	Y	55%
Grip	N	18%	N	18%	N	9%
ECU	N	27%	N	45%	Y	36%
ED	Y	73%	Y	73%	Y	82%
ECR	Y	91%	Y	100%	Y	100%
FCU	Y	100%	Y	91%	Y	100%
FCR	Y	91%	Y	91%	Y	100%
FDS	Y	100%	Y	100%	Y	100%
FPL	Y	73%	Y	73%	Y	73%
FDI	Y	82%	N	9%	Y	91%
Avg EMG		80%		73%		85%

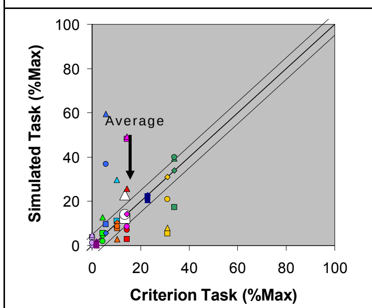


Figure E17-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

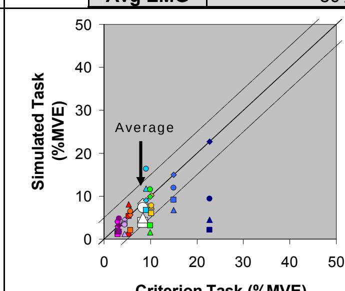


Figure E17-17: Comparison of task simulations within a ±5% range of criterion task for ED

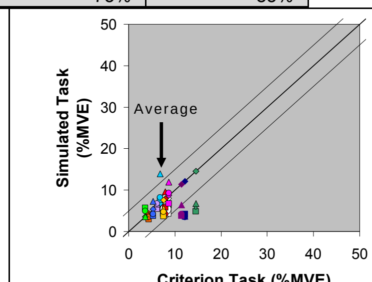


Figure E17-18: Comparison of task simulations within a ±5% range of criterion task for FPL

18. Power Steering Hose Summary

- Apply push force of 16N using a modified pulp pinch
- Upward force of 1.5N

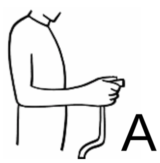


Figure E18-1:

Criterion task: Insert hose on radiator

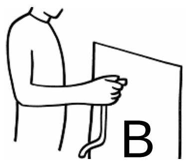


Figure E18-2:

Real parts with simple feedback: Push hose against constant force

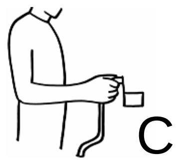


Figure E18-3:

Real parts with force and moment feedback: Hose insertion simulated with a hose fixed to a force transducer

Figure E18-4:

Simplified parts with force and moment feedback: Hose insertion simulated with a 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to the forces and moments required to insert a hose (Table E18-1).
- **Posture:** The criterion task (A) required flexion, all other simulations (B, C, D6) required significantly more extension.
- **Perceived Effort:** The perceived effort for the criterion task (A) was significantly greater then that of the constant force simulation (B) and the horizontal pinch simulation (D6) (Figure E18-6).
- **Grip Force Matching:** No significant differences in grip force matching were determined (Figure 7).
- **Muscle Activation:** Significant differences in muscle activation between inserting a real hose (A) and each simulation were found (Figures E18-8 to E18-15).
  - o A vs. B: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓
  - o A vs. C: ECR↓, FCU↓, FCR↓, FDS↓, FPL↓
  - o A vs. D6: ECU↓, ED↓, ECR↓, FCU↓, FCR↓, FDS↓, FPL↓
- An ‘*’ on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E18-1: Applied forces

Task	Push Force (N)	Upward Force (N)
A*	16	1.5
B	16	1.5
C	13.9 ± 4.98	3.4 ± 2.37
D6	14.9 ± 1.15	1.5 ± 1.60

* This task is a real hose insertion used to calculate forces. Participants were required to match within +/-10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E18-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D6
Perceived effort	0.64	0.73	0.78

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic task
- Changes in degrees of freedom
- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface
- Obstrcutions

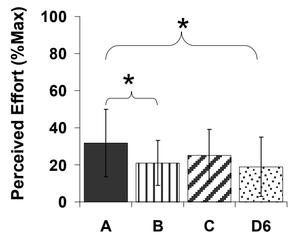


Figure E18-6: Perceived effort

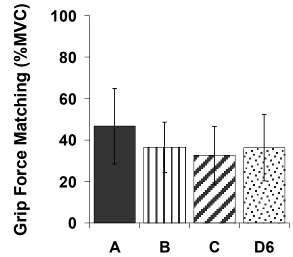


Figure E18-7: Grip strength matching

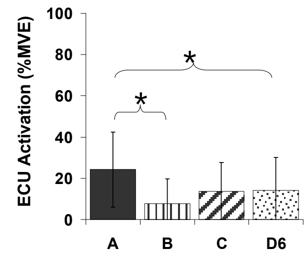


Figure E18-8: ECU %MVE

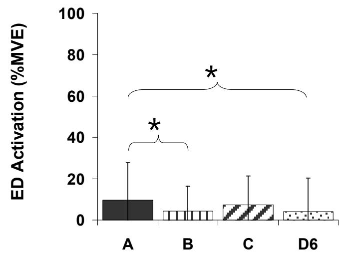


Figure E18-9: ED %MVE

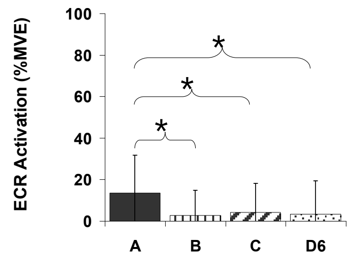


Figure E18-10: ECR %MVE

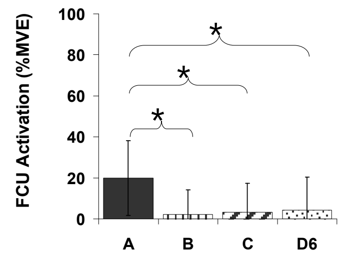


Figure E18-11: FCU %MVE

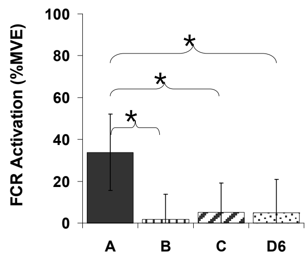


Figure E18-12: FCR %MVE

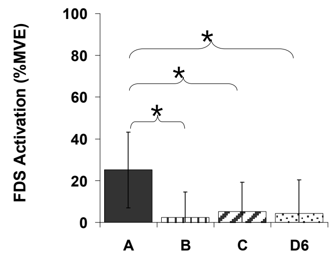


Figure E18-13: FDS %MVE

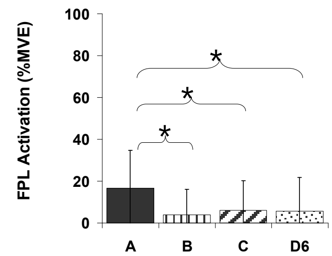


Figure E18-14: FPL %MVE

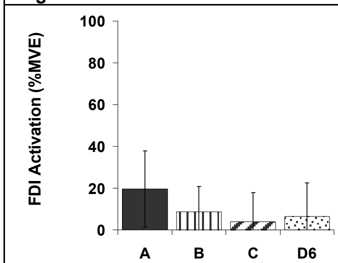


Figure E18-15: FDI %MVE

Table E18-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D6 ○	
Perceived Effort	N	45%	N	45%	N	27%
Grip	N	9%	N	27%	N	9%
ECU	N	0%	N	9%	N	18%
ED	N	36%	Y	55%	N	45%
ECR	N	18%	N	18%	N	27%
FCU	N	9%	N	9%	N	18%
FCR	N	9%	N	9%	N	9%
FDS	N	9%	N	9%	N	9%
FPL	N	9%	N	36%	N	36%
FDI	N	45%	N	0%	N	45%
Avg		47%		42%		49%

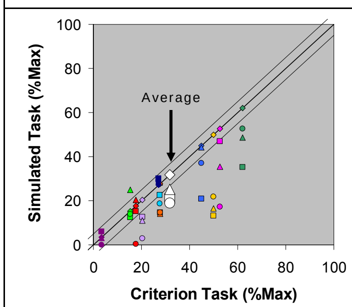


Figure E18-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

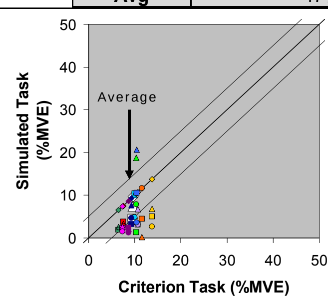


Figure E18-17: Comparison of task simulations within a ±5% range of criterion task for ED

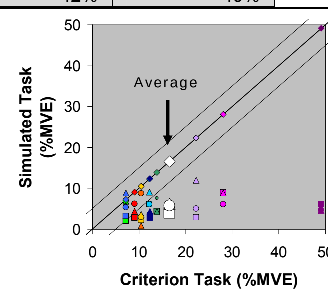


Figure E18-18: Comparison of task simulations within a ±5% range of criterion task for FPL

19. Fastener Init. Neutral Summary	• Apply palmar force of 1.0N using a pulp pinch • Apply ulnar moment of 0.03Nm

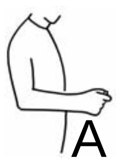


Figure E19-1: Criterion task: Turn nut on bolt, rotated 90º from task Q

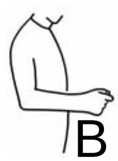


Figure E19-2: Real parts with simple feedback: Turn nut rotated 90º from task Q against constant force and moment

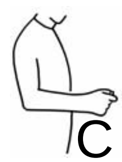


Figure E19-3: Real parts with force and moment feedback: Nut turn with 90º rotation from task Q simulated with a nut fixed to a force transducer

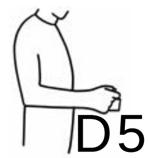


Figure E19-4: Simplified parts with force and moment feedback: Nut rotation simulated with a 25mm handle parallel to the axis of the forearm fixed to a force transducer

Figure E19-5: Simplified parts with force and moment feedback: Nut rotation simulated with a 25mm handle perpendicular to the axis of the forearm fixed to a force transducer

- **Forces:** Participants used visual feedback to match the forces and moments required to turn the nut (Table E19-1).
- **Posture:** The simulation with the constant force and moment (B) required significantly more ulnar deviation then the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort between turning a real nut (A) and the simulations were found (Figure E19-6).
- **Grip Force Matching:** No significant differences in grip force matching between turning a real nut and simulating this were found (Figure E19-7).
- **Muscle Activation:** Significant differences in muscle activation between turning a real nut (A) and each simulation were found (Figures E19-8 to E19-15).
  - A vs. B: FCR↓, FDS↓
  - A vs. C: ECU↓, ED↓, FCR↓, FDS↓
  - A vs. D5: FCR↓, FDS↓, FDI↓
  - A vs. D6:
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table E19-1: Applied forces and moments

Task	Palmar Force (N)	Supinator Moment (Nm)
A*	1	0.03
B	1	0.03
C	1.09 ± 1.36	0.031 ± 0.04
D5	-1.19 ± 0.77	-0.031 ± 0.12
D6	-0.34 ± 0.94	-0.012 ± 0.12

* This task is a real nut turn used to calculate forces and moments. Participants were required to match within +/-10% of these values.

Intraclass Correlation Coefficients (ICC):

Table E19-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D5	A-D6

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Dynamic manual task
- Different wrist posture
- Different sized handle
- Different shaped handle
- Different material surface

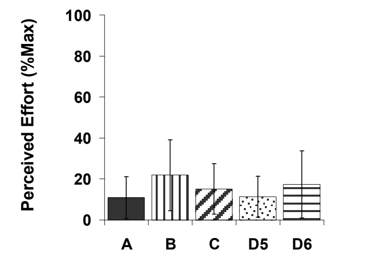


Figure E19-6: Perceived effort

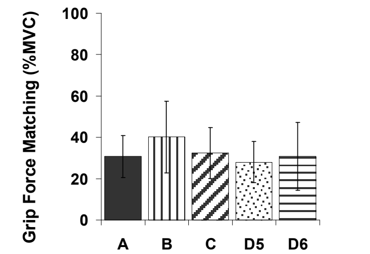


Figure E19-7: Grip strength matching

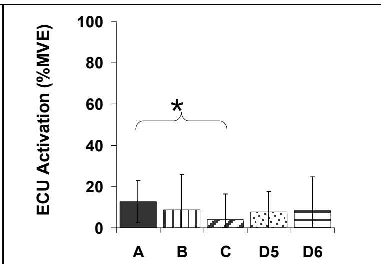


Figure E19-8: ECU %MVE

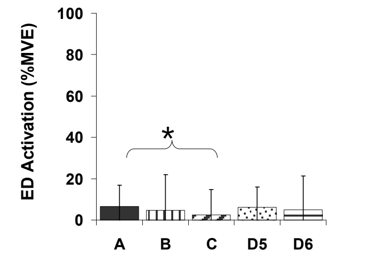


Figure E19-9: ED %MVE

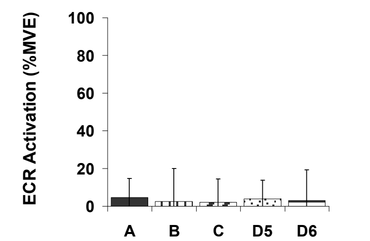


Figure E19-10: ECR %MVE

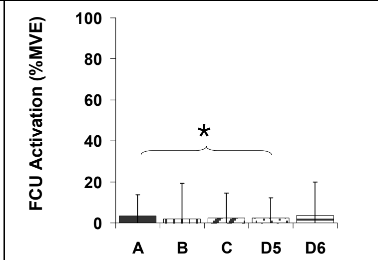


Figure E19-11: FCU %MVE

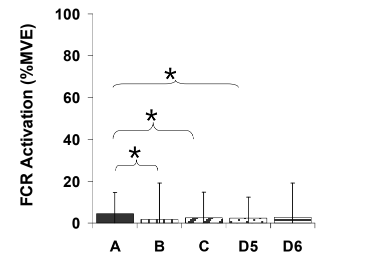


Figure E19-12: FCR %MVE

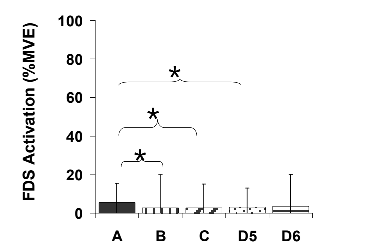


Figure E19-13: FDS %MVE

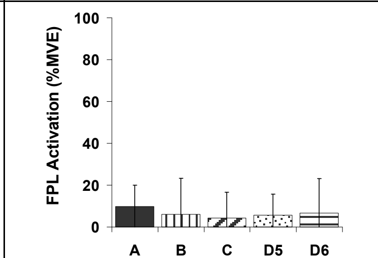


Figure E19-14: FPL %MVE

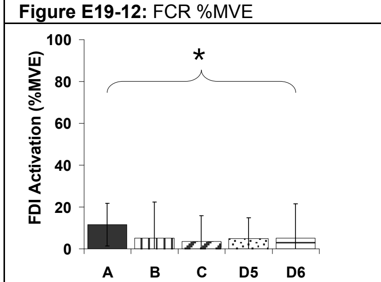


Figure E19-15: FDI %MVE

Table D-S 3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants' falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D5 ○		D6 +	
Perceived Effort	N	36%	Y	64%	Y	45%	N	18%
Grip	N	9%	Y	55%	Y	36%	Y	18%
ECU	Y	45%	N	27%	Y	45%	Y	73%
ED	Y	91%	Y	64%	Y	73%	Y	73%
ECR	Y	91%	Y	73%	Y	91%	Y	91%
FCU	Y	82%	Y	82%	Y	100%	Y	73%
FCR	Y	91%	Y	82%	Y	91%	Y	100%
FDS	Y	82%	Y	82%	Y	91%	Y	82%
FPL	Y	64%	N	55%	Y	55%	Y	64%
FDI	N	45%	N	0%	N	55%	N	64%
Avg EMG		64%		58%		68%		65%

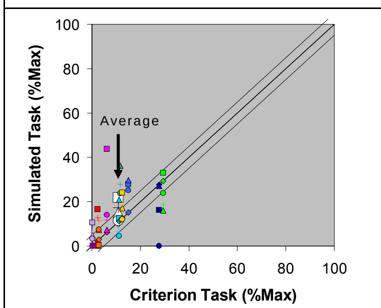


Figure E19-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

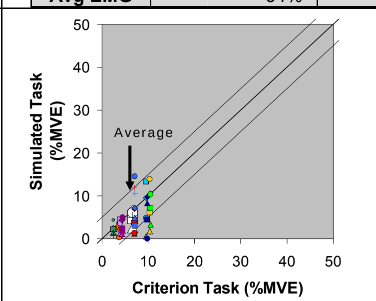


Figure E19-17: Comparison of task simulations within a ±5% range of criterion task for ED

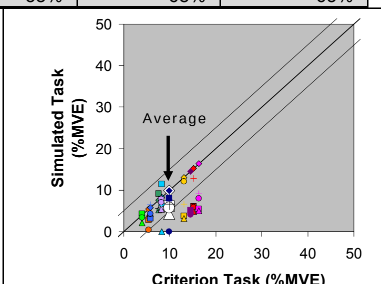


Figure E19-18: Comparison of task simulations within a ±5% range of criterion task for FPL

20. Brake Line Cap Removal Summary	• Apply upward force of 10.20N using a pulp pinch

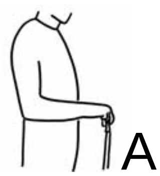


Figure D20-1: Criterion task: Pull brake line cap from brake line

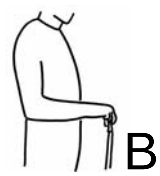


Figure D20-2: Real parts with simple feedback: Cap pull simulated with a constant force

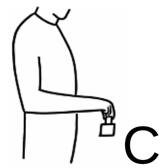


Figure D20-3: Real parts with force and moment feedback: Cap pull simulated with a cap attached to a force transducer

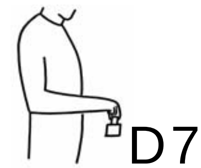


Figure D20-4: Simplified parts with force and moment feedback: Cap pull simulated with a vertical 25mm handle fixed to a force transducer

Figure D20-5: Simplified parts with force and moment feedback: Cap pull simulated with a horizontal 25mm handle fixed to a force transducer

- **Forces:** Participants used visual feedback to match the force required to simulate a brake line cap pull (Table E20-1).
- **Posture:** The simulation with the vertical handle (D7) required significantly less ulnar deviation and extension than the criterion task (A). The simulation with the horizontal handle (D6) required significantly less extension than the criterion task (A).
- **Perceived Effort:** No significant differences in perceived effort between the real task and the simulations were found (Figure E20-6).
- **Grip Force Matching:** No significant differences in grip force matching between the real task and the simulations were found (Figure E20-7).
- **Muscle Activation:** Significant differences in muscle activation between pulling a real cap from brake line (A) and each simulation were found (Figures E20-8 to E20-15).
    - A vs. B:
    - A vs. C: FCU↓
    - A vs. D7: FCU↓, FDS↓
    - A vs. D6: FCU↓, FCR↓
- An '*' on these figures indicates a significant difference between the muscle activation of the simulation and the real task determined using a repeated measures ANOVA and a Dunnett post-hoc at the .05 level.

Table D20-1: Applied forces and moments

Task	Upward Force (N)
A*	10.2
B	10.2
C	9.45 ± 2.56
D7	9.28 ± 1.18
D6	9.28 ± 1.19

* This task is a real cap pull used to calculate forces. Participants were required to match within +/-10% of this value.

Intraclass Correlation Coefficients (ICC):

Table D20-2: Comparison of ICC between the criterion task and each simulation

	A-B	A-C	A-D7	A-D6

Possible sources of these differences:
(Refer to Table 2 in main body for more detail)

- Different wrist posture[1]
- Different sized handle[4]
- Different shaped handle[8]
- Different material surface[6]

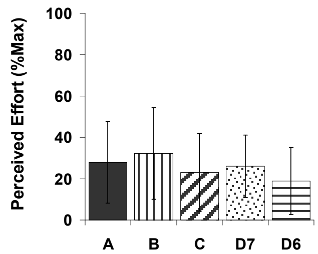


Figure E20-6: Perceived effort

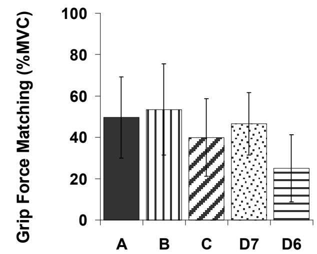


Figure E20-7: Grip strength matching

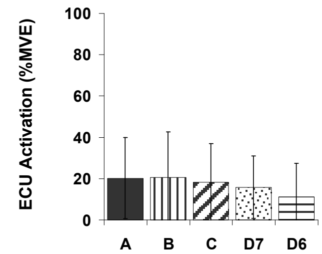


Figure E20-8: ECU %MVE

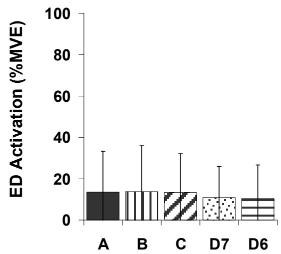


Figure E20-9: ED %MVE

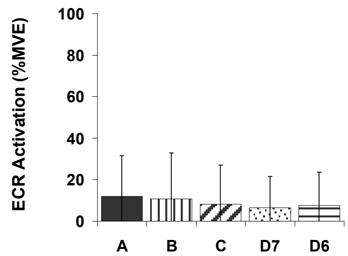


Figure E20-10: ECR %MVE

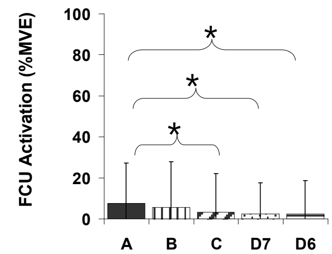


Figure E20-11: FCU %MVE

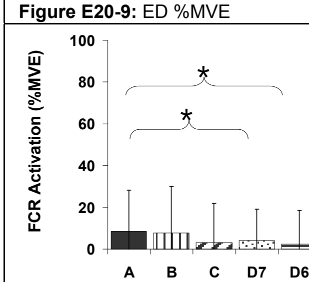


Figure E20-12: FCR %MVE

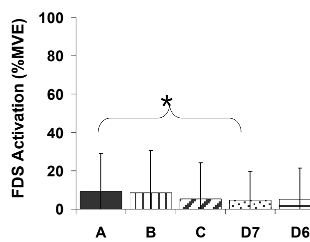


Figure E20-13: FDS %MVE

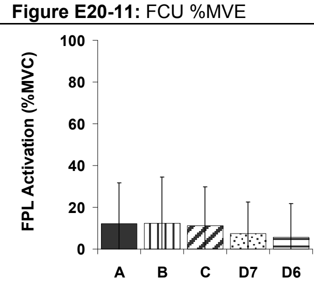


Figure E20-14: FPL %MVE

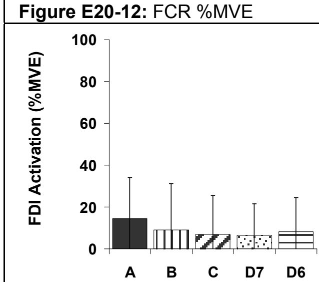


Figure E20-15: FDI %MVE

Table E20-3: Comparison of the average number of parameters within ±5% of the real task: Y indicates the average value of all participants falls within this range, N indicates it does not, % indicates the number of participants for which this is true.

A ◇	B □		C △		D7 ○		D6 +	
Perceived Effort	Y	55%	Y	45%	Y	27%	N	36%
Grip	Y	55%	N	36%	Y	36%	N	36%
ECU	Y	45%	Y	27%	Y	36%	N	36%
ED	Y	55%	Y	64%	Y	45%	Y	36%
ECR	Y	64%	Y	64%	N	55%	Y	73%
FCU	Y	64%	Y	73%	N	64%	N	64%
FCR	Y	73%	N	73%	Y	64%	N	64%
FDS	Y	73%	Y	55%	Y	36%	Y	45%
FPL	Y	45%	Y	73%	Y	64%	N	64%
FDI	N	64%	N	18%	N	45%	N	55%
Avg EMG		59%		53%		47%		51%

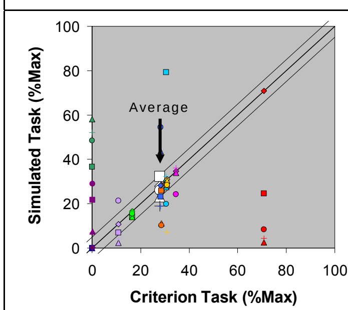


Figure E20-16: Comparison of task simulations within a ±5% range of criterion task for perceived effort

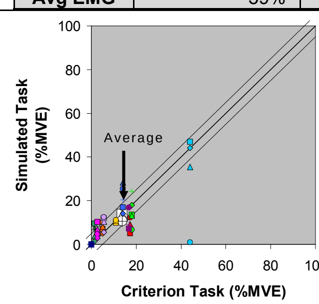


Figure E20-17: Comparison of task simulations within a ±5% range of criterion task for ED

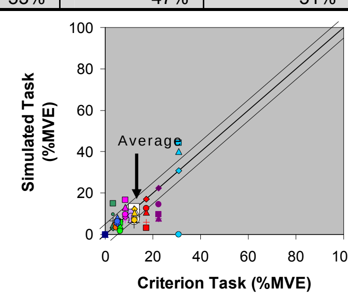


Figure E20-8: Comparison of task simulations within a ±5% range of criterion task for FPL

Appendix F

Summary of simulation method results

Figure F1: Comparison of the average ICC across each simulation type for all tasks (higher values indicate a better correlation)

	Perceived Effort			Grip force matching			EMG (Average)		
Task	A-B	A-C	A-D	A-B	A-C	A-D	A-B	A-C	A-D
1		0.42	0.16		0.55	0.34		0.58	0.41
2		0.67	0.41		0.65	0.27		0.58	0.43
3		0.88	0.47		0.95	0.77		0.52	0.27
4		0.40	0.10		0.85	-0.06		0.15	0.14
5	0.71	0.8	0.14	0.6	0.63	0.78	0.23	0.14	0.28
6	0.36	0.58	0.33	0.45	0.79	0.74	0.08	0.13	0.06
7	0.49	0.8	0.76	0.82	0.62	0.81	0.44	0.31	0.43
8	0.32	0.48	0.61	0.71	0.74	0.81	0.79	0.4	0.59
9	0.58	0.35	0.49	0.78	0.14	0.61	0.44	0.13	0.36
10	0.76	0.17	0.72	0.74	0.55	0.42	0.64	0.18	0.36
11	0.5	0.71	0.7	0.75	0.46	0.82	0.67	0.61	0.53
12	0.59	0.38	0.7	0.78	0.78	0.87	0.61	0.4	0.32
13	0.24	0.26	0.37	0.62	0.06	0.35	0.23	0.4	0.39
14	0.5	0.81	0.69	0.24	0.8	0.74	0.25	0.3	0.24
15	0.85	0.62	0.4	0.77	0.61	0.06	0.54	0.71	0.35
16	0.55	0.61	0.32	0.07	0.54	-0.33	0.2	0.5	0.38
17	0.28	0.17	0.64	0.11	0.22	-0.09	0.36	0.39	0.47
18	0.64	0.73	0.78	0.66	0.87	0.76	0.17	0.13	0.09
19	0.31	0.64	0.18	0.18	0.36	0.51	0.35	0.19	0.38
20	0.32	-0.08	-0.12	0.76	0.81	0.63	0.5	0.45	0.14
Average	0.50	0.52	0.44	0.57	0.60	0.49	0.41	0.36	0.33

Figure F2: Comparison of the average number of significant differences as determined using a repeated measures ANOVA ($p<0.05$) (lower values indicate fewer differences)

	Perceived Effort			Grip force matching			EMG (Average)		
Task	A-B	A-C	A-D	A-B	A-C	A-D	A-B	A-C	A-D
1		0	0		0	0		1	3
2		0	0		1	0		4	4
3		0	0		0	0		0	2
4		0	0		0	0		3	3
5	0	0	0	0	0	0	7	4	8
6	0	0	0	0	0	0	4	8	5
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	3	3
9	0	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	0	0
11	0	1	0	0	1	1	0	0	0
12	0	0	0	0	0	0	0	3	3
13	0	0	0	1	1	0	5	0	0
14	0	0	0	1	1	0	5	0	0
15	0	0	0	0	0	0	0	0	2
16	0	0	0	0	0	0	0	0	2
17	0	0	0	0	0	0	7	2	4
18	0	0	0	1	0	0	7	5	7
19	0	0	0	0	0	0	2	4	0
20	0	0	0	0	0	0	0	1	2
Average	0.00	0.05	0.00	0.19	0.20	0.05	2.31	1.95	2.40

Figure F3: Comparison of the average number of parameters within ±5% of the criterion task (higher values indicate more parameters within range)

	Perceived Effort			Grip force matching			EMG (Average)		
Task	A-B	A-C	A-D	A-B	A-C	A-D	A-B	A-C	A-D
1		0	0		0	1		0	0
2		0	0		1	0		1	1
3		0	0		1	0		1	1
4		0	0		0	1		0	0
5	1	1	0	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0
7	0	1	1	0	1	1	1	1	1
8	0	1	0	1	0	1	1	1	1
9	1	0	0	1	1	0	1	0	0
10	1	1	1	0	0	0	1	1	1
11	0	0	0	0	0	0	1	1	1
12	0	0	1	0	0	0	1	0	0
13	1	1	1	0	0	0	0	1	1
14	1	1	1	0	0	0	0	1	1
15	1	1	0	0	0	0	1	1	1
16	0	0	0	1	0	1	1	1	0
17	1	0	1	0	0	0	1	1	1
18	0	0	0	0	0	0	0	0	0
19	0	1	0	0	1	1	1	1	1
20	1	1	0	1	0	0	1	1	0
Average	0.50	0.45	0.30	0.31	0.30	0.35	0.75	0.70	0.60

Figure F4: Comparison of the average number of parameters within ±10% of the criterion task (higher values indicate more parameters within range)

Average number of parameters within ±10% of most realistic (High = Good)									
	Perceived Effort			Grip force matching			EMG (Average)		
Task	A-B	A-C	A-D	A-B	A-C	A-D	A-B	A-C	A-D
1		0	0		1	1		0	1
2		1	0		0	1		1	1
3		1	1		1	1		1	1
4		1	1		1	1		1	0
5	1	1	1	1	1	1	1	1	1
6	1	1	0	1	0	0	0	0	0
7	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1
11	1	0	1	1	0	0	1	1	1
12	1	1	1	0	1	1	1	1	1
13	1	1	1	0	0	0	1	1	1
14	1	1	1	0	0	0	1	1	1
15	1	1	0	1	1	0	1	1	1
16	1	0	1	1	1	1	1	1	1
17	1	1	1	0	0	1	1	1	1
18	0	1	0	0	0	0	0	0	0
19	0	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1
Average	0.88	0.85	0.75	0.69	0.65	0.70	0.88	0.85	0.85

Figure F5: Comparison of the rank of each simulation type based on the method of analysis to determine which one is best

Best Simulation		3 pts	2 pts	1 pt
Based on perceived effort	ICC	C	B	D
	ANOVA	B,D	C	
	±5%	B	C	D
Based on grip force matching	ICC	C	B	D
	ANOVA	D	B	C
	±5%	D	B	C
Based on EMG	ICC	B	C	D
	ANOVA	C	B	D
	±5%	B	C	D
Total Points	B = 22	C = 19	D = 15	

Appendix G

Summary of simulation method results

Comparison of task rankings for each simulation for all measured parameters:

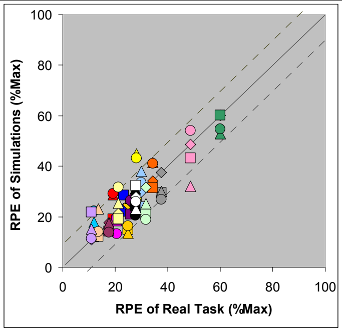


Figure G1: Perceived effort comparison between all tasks

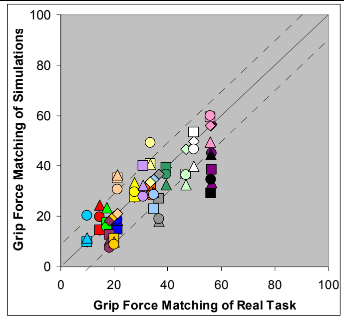


Figure G2: Grip force matching comparison between all tasks

Looking at task rankings:

- Tasks were ranked in order of magnitude for each of the measured parameters (1=highest).
- Figures G1 to G10 show the relative ranking of each task for each simulation.
- This ranking was correlated between the real task and each of the simulations.
- Table G1 shows these correlations.

Choosing the best parameter:

- Looking at the average correlation coefficient of all simulations, the usefulness of each of the measured parameters can be determined.
- The parameters with the highest average correlation coefficients across all simulations are ranked

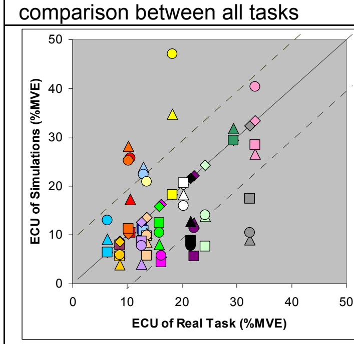


Figure G3: ECU %MVE comparison between all tasks

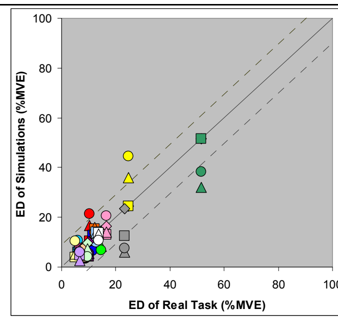


Figure G4: ED %MVE comparison between all tasks

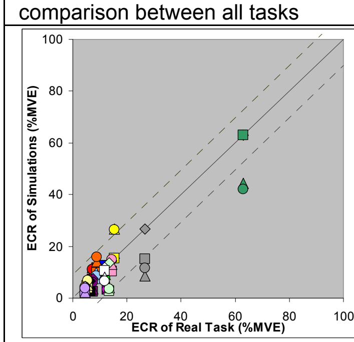


Figure G5: ECR %MVE comparison between all tasks

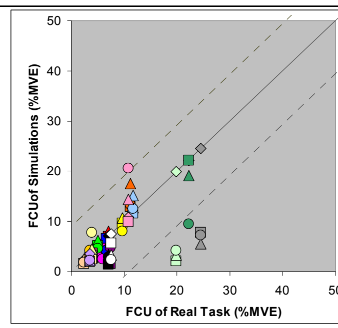


Figure G6: FCU %MVE comparison between all tasks

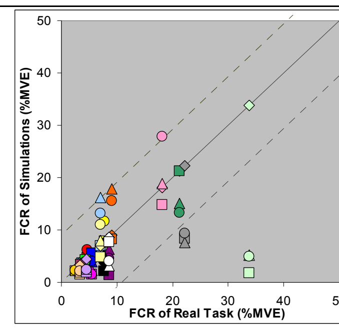


Figure G7: FCR %MVE comparison between all tasks

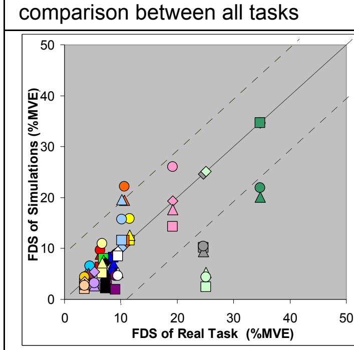


Figure G8: FDS %MVE comparison between all tasks

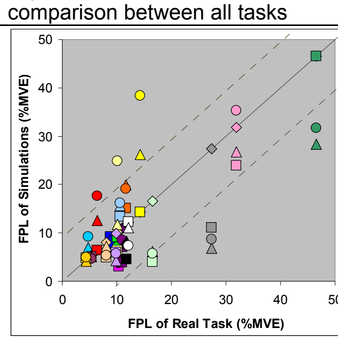


Figure G9: FPL %MVE comparison between all tasks

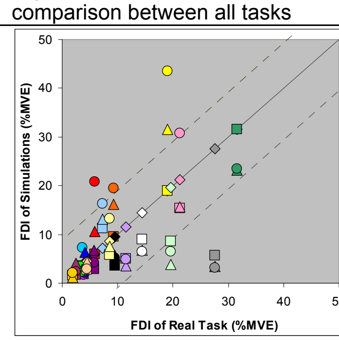


Figure G10: FDI %MVE comparison between all tasks

Comparison of rank correlation between the criterion task and each simulation for all measured parameters :

Legend

Real task

Simulation with real parts and simple feedback

Simulation with real parts and force and moment feedback

Simulation with simplified parts and force and moment feedback

1	Sledge hammer hold	
2	22oz hammer hold	
3	16oz hammer hold	
4	Modified heavy hammer hold	
5	Rad. hose insertion	
6	Window seal insertion using pizza wheel	
7	Large drill hold	
8	Large drill push	
9	Large drill push & turn	
10	Small drill hold	
11	Small drill push	
12	Small drill push & turn	
13	Wire harness (ORC1, wires)	
14	Wire harness (ORC2, no wires)	
15	Plate Hold 0.5kg	
16	Plate Hold 2.2kg	
17	Fastener init. extended	
18	Power steering hose	
19	Fastener init. neutral	
20	Brake line cap	

Figure G11: Comparison of the correlation between the criterion task and each simulation for all measured parameters

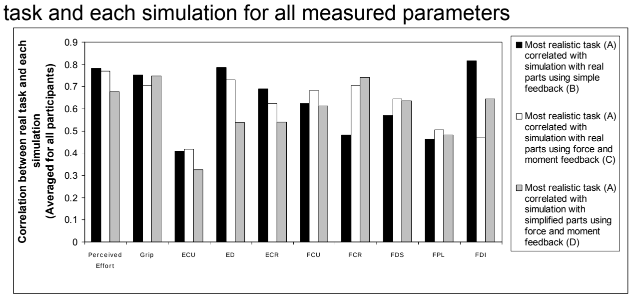


Table G1: Correlation of task ranking for each simulation and each parameter

Ranking Comparison to the criterion task (A) using correlations (Spearman's correlation coefficient)						
	B	**C**	**D**	**Rank**	**Avg**	**St Dev.**
Perceived Effort	0.783	0.770	0.678	1	0.74	0.06
Grip	0.752	0.704	0.747	2	0.73	0.03
ECU	0.409	0.418	0.325	10	0.38	0.05
ED	0.786	0.731	0.537	3	0.68	0.13
ECR	0.689	0.623	0.541	7	0.62	0.07
FCU	0.624	0.681	0.612	6	0.64	0.04
FCR	0.483	0.704	0.741	5	0.64	0.14
FDS	0.571	0.644	0.636	8	0.62	0.04
FPL	0.463	0.505	0.483	9	0.48	0.02
FDI	0.817	0.469	0.645	4	0.64	0.17
EMG Avg	0.61	0.60	0.57		**0.59**	
St. Dev.	0.15	0.12	0.13		**0.10**	

B. Real parts with simple feedback
C. Real parts with force moment feedback
D. Simplified parts with force and moment feedback

Appendix H

Comparison of demand determined using normative data with that measured from manual tasks and simulations

Task	Direction of Force or Moment (N or Nm)	Normative Data		Simulation		
		Hand Capability* (N or Nm)	Relative Demand (%Max)		RPE (%Max)	Grip Force Matching (%MVC)
Task 1: Sledge Hammer Hold	Upward Force: 20	194.6	10	A	28	28
				B	-	-
	Radial deviator moment: 5.73	10.3	**56**	C	45	33
				D	43	30
Task 2: 22oz hammer hold	Upward Force: 10	194.6	5.1	A	19	14
				B	-	-
	Radial deviator moment: 1.95	10.3	**19**	C	29	25
				D	29	20
Task 3: 16oz hammer hold	Upward Force: 7.20	194.6	3.7	A	12	10
				B	-	-
	Radial deviator moment: 0.93	10.3	**9.0**	C	18	11
				D	22	20
Task 4: Modified heavy hammer hold	Upward Force: 83	194.6	**43**	A	60	39
				B	-	-
	Radial deviator moment: 1.95	10.3	19	C	53	33
				D	55	37
Task 5: Radiator hose insertion	Push force: 13	113.6	**11**	A	21	19
				B	18	18
	Upwards force: 3.43	194.6	1.7	C	19	17
				D	13	14
Task 6: Window seal insertion	Dorsal force: 10	74.4	**13**	A	38	37
				B	30	27
	Upwards force: 26	194.6	**13**	C	30	18
				D	27	19
Task 7: Large drill hold				A	23	21
	Upwards force: 23.2	194.6	**12**	B	29	15
				C	23	19
				D	22	19
Task 8: Large drill push	Upwards force: 23.2	194.6	**12**	A	27	17
				B	21	17
	Push force: 5.0	113.6	4.4	C	27	23
				D	21	16

Task	Direction of Force or Moment (N or Nm)	Normative Data: Hand Capability* (N or Nm)	Normative Data: Relative Demand (%Max)	Simulation	Simulation: RPE (%Max)	Simulation: Grip Force Matching (%MVC)
Task 9: Large drill push and turn	Upwards force: 23.2	194.6	12	A	34	34
	Push force: 5.0	113.6	4.4	B	31	31
	Pronator moment: 3.5	8.1	**43**	C	41	30
				D	41	28
Task 10: Small drill hold	Upwards force: 7.4	194.6	**3.8**	A	18	18
				B	14	13
				C	17	11
				D	14	8
Task 11: Small drill push	Upwards force: 7.4	194.6	3.8	A	25	20
				B	15	11
				C	13	10
	Push force: 5.0	113.6	**4.4**	D	16	9
Task 12: Small drill push & turn	Upwards force: 7.4	194.6	3.8	A	30	35
	Push force: 5.0	113.6	4.4	B	24	23
	Pronator moment: 3.0	8.1	**37**	C	38	30
				D	34	29
Task 13: Wire harness (ORC1, wires)	Push force: 15	105	**14**	A	26	56
				B	21	39
				C	27	33
				D	26	45
Task 14: Wire harness (ORC2, no wires)	Push force: 15	105	**14**	A	28	56
				B	24	29
				C	31	45
				D	21	35
Task 15: Plate hold 0.5kg	Upwards force: 6.9	154	4.5	A	21	34
				B	19	41
	Radial deviator moment: 0.6	3.0	**20**	C	25	41
				D	32	49
Task 16: Plate hold 2.2kg	Upwards force: 24	154	4.5	A	49	56
				B	43	59
				C	32	50
	Radial deviator moment: 2	3.0	**20**	D	54	60

Task	Direction of Force or Moment (N or Nm)	Normative Data Hand Capability* (N or Nm)	Normative Data Relative Demand (%Max)	Simulation	RPE (%Max)	Grip Force Matching (%MVC)
Task 17: Fastener initiation extended posture	Palmar force: 1.0	42.2	**2.4**	A	14	21
				B	12	35
	Supinator moment: 0.03	2.4	1.3	C	23	36
				D	14	31
Task 18: Power steering hose	Push force: 16	105	**15**	A	32	47
				B	21	37
	Upwards force: 1.5	154	0.01	C	25	33
				D	19	36
Task 19: Fastener initiation neutral posture	Palmar force: 1.0	42.2	**2.4**	A	11	31
				B	22	40
	Ulnar moment: 0.03	2.6	1.1	C	15	32
				D	11	28
Task 20: Brake line cap removal	Upward force: 10.2	100	**10**	A	28	50
				B	32	53
				C	23	40
				D	26	47

* Hand capability normative data from Greig & Wells (2004)

Appendix I

Comparison of the difference between two repetitions of the same task

Table H1: Comparison of two repetitions of the same task for perceived effort, grip force estimation, and the muscle activation of extensor carpi ulnaris (ECU), extensor digitorum (ED) and extensor carpi radialis (ECR)

	Perceived Effort		Grip		ECU		ED		ECR	
Participant	Percent Difference (%)	Absolute Difference (%Max)	Percent Difference (%)	Absolute Difference (%MVC)	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)
DAR	47	8	90	13	59	6	95	7	82	10
CHK	46	10	46	6	42	5	36	7	24	6
ES	24	11	75	36	45	10	33	3	17	3
WH	48	5	44	10	105	16	67	4	47	2
MHJ	76	6	39	6	48	5	28	2	38	3
AA	52	16	0	9	50	6	43	4	51	5
MC	78	15	133	28	70	8	85	10	63	8
DM	58	5	106	19	50	9	27	4	12	1
RQ	99	10	99	16	21	1	21	1	23	2
TC	49	18	50	19	34	4	37	7	33	3
Average	**58**	**10**	**68**	**16**	**52**	**7**	**47**	**5**	**39**	**4**

Table H2: Comparison of two repetitions of the same task for the muscle activation of flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), flexor digitorum superficialis (FDS) and the first dorsal interosseus (FDI)

	FCU		FCR		FDS		FPL		FDI	
Participant	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)	Percent Difference (%)	Absolute Difference (%MVE)
DAR	56	4	87	5	83	5	34	4	86	6
CHK	43	3	34	3	38	3	27	6	64	7
ES	37	3	21	0	16	2	17	2	110	23
WH	64	7	76	3	74	4	58	4	82	7
MHJ	43	2	52	4	34	4	22	3	44	0
AA	47	2	40	3	46	5	62	10	48	1
MC	94	6	84	4	101	10	83	9	80	17
DM	44	2	38	2	33	4	129	7	55	2
RQ	28	2	18	1	42	8	25	2	65	9
TC	46	8	43	5	34	3	45	6	62	14
Average	**50**	**4**	**49**	**3**	**50**	**5**	**50**	**5**	**70**	**9**