Performance of a two-foot vertical jump:
What is more important hip or knee dominance?

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Vertical jumping ability is an important fundamental skill for many athletic activities. The present work is focused on developing an understanding of the role of various movement strategies on vertical jump performance. The overall objective of this study was to determine if higher hip than knee joint contribution was more effective in enhancing vertical jump height. Additionally, the study explored possible links between the muscle activity and mechanical outputs, and to develop understanding of the role of the lumbar spine and hip. Twenty male university varsity athletes performed ten repetitions of three jumping strategies: preferred, hip dominant and knee dominant. Kinematics, kinetics and muscle activity of the lower limb and trunk were collected.

The main observation was that the vertical jump height was positively associated with higher hip than knee work done. However, the within-subject comparisons between the trained hip and knee dominant tasks did not provide additional support for the importance of the hip. Higher hip work appeared associated with greater biceps femoris than gluteus maximus activity. The knee work increased with higher activity of the vastus lateralis and rectus femoris. Finally, higher trunk muscle activity and tighter coupling were associated with the vertical jump height and the max force. This study provides some evidence that encouraging hip dominance together with higher spine stiffness may improve two-foot vertical jump performance. This work has potential implications for training protocols that may be used to improve vertical jump performance.

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List of Abbreviations

ATP	adenosine triphosphate
BFem	biceps femoris
BOS	base of support
CNS	central nervous system
COM	centre of mass
CMJ	countermovement jump
EMG	electromyography
EO	external oblique
Gas	gastrocnemius
GMax	gluteus maximus
GRF	ground reaction force
IEMG	integrated electromyography
IO	internal oblique
MVC	maximum voluntary contraction
PCA	physiologic cross-sectional area
RA	rectus abdominis
RFD	rate of force development
RFem	rectus femoris
RFR	rate of force relaxation
RPE	rate of perceived exertion
SERCA	sarco/endoplasmic reticulum Ca^{2+}-ATPase
SJ	squat jump
TO	take-off
TOV	take-off velocity
UES	upper erector spinae

VLat	vastus lateralis
ZeroV	zero velocity

1. Introduction

Improving performance in movement behaviours is a common objective for a variety of populations and for a variety of tasks. For example skill acquisition is not only essential for optimizing athletic performance but also necessary to improve movement control after injury. Physical training is a means to improve performance and the optimization of training protocols is often the objective of coaches and trainers. The overall objective of this study was to develop understanding that may help guide training protocols to enhance movement performance, specifically the ability to vertically jump.

The movement of interest was a standing single two-foot countermovement vertical jump with arm swing; from herein vertical jump refers to the specific type used in this study. The rationale for selecting this movement task are: 1) it is an important performance factor for sports and athletic activities, 2) there is a lack of full understanding of control mechanisms that if better understood would benefit the design of training protocols, and 3) control challenges of this behaviour are also unique. Furthermore, the incorporation of the countermovement and arm swing does not restrict the participant in their attempt to achieve a maximum jump height.

To accomplish our overall objective we must initially understand the factors that influence the vertical jump performance. The figure below (Figure 1) displays a theoretical framework of factors that may be important. The current thesis focuses on the motor strategy as a factor for improving vertical jumping (denoted CNS Motor Strategy on the Framework), because its importance remains unresolved in the literature. We are specifically interested in the strategy that involves a higher contribution of a single lower limb joint and its influence on jumping performance. This lays out the main hypotheses that we seek to test:

1. Jumping performance will improve with a greater involvement of the hip than the knee and ankle.
2. The mono-articular muscles of the hip and knee will be more important than the bi-articular muscles in maximizing each joint's mechanical outputs.
3. Hip kinematics will improve by having reduced motion at the lumbar spine; the lumbar spine will act as a fixed point (punctum fixum), to improve the hip kinematics.

The results from our testing may inform athletes, trainers and coaches to modify existing exercise protocols and jump movement-related drills that encourage a single-joint's dominance or multi-joint coupling.

It is noteworthy that while we investigate the strategy as being an important determinant of jumping performance, there are a number of intervening variables that may influence/contribute to take-off velocity and the line of force application that ultimately determine vertical jump performance. These include anthropometry, muscle physiology, storage and recovery of elastic energy, and spine stability. The following sections form a review of the relevant literature unified around the sub-components identified in this framework, with the last section detailing the importance and rationale for the motor strategy in jumping performance.

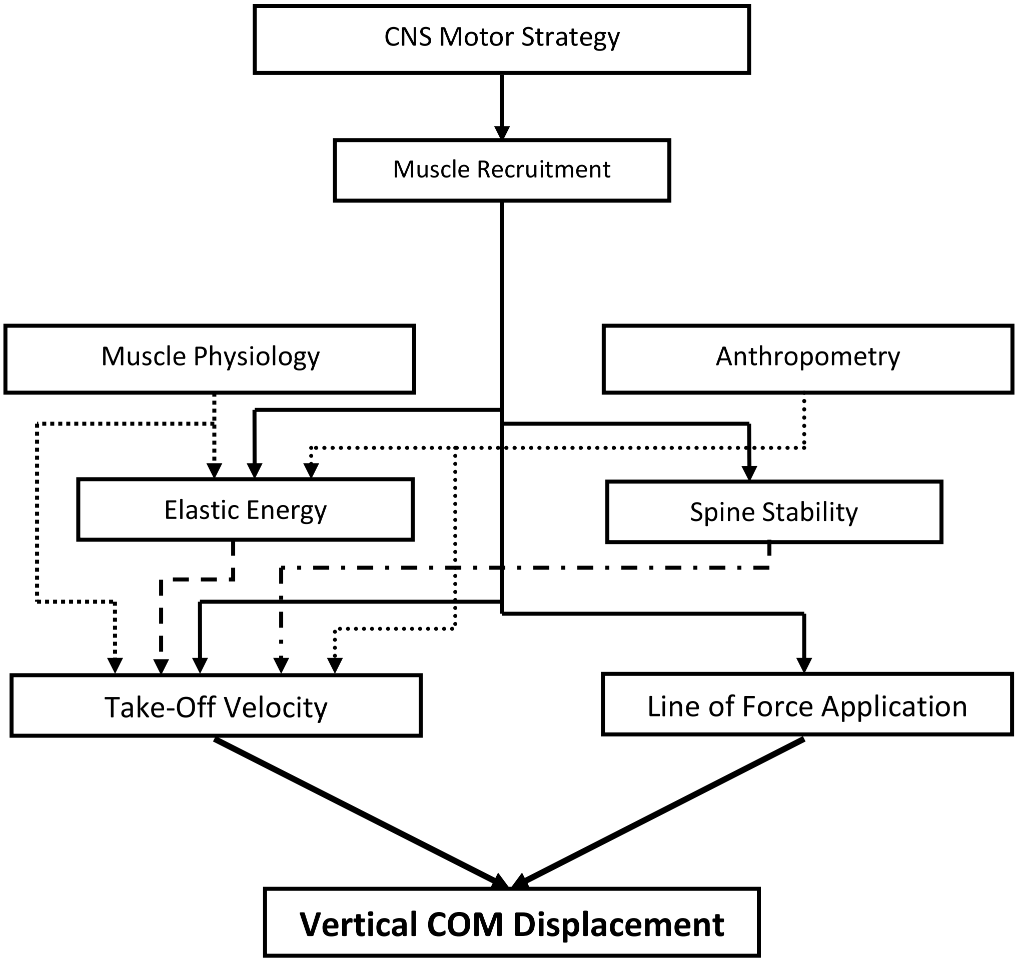

Figure 1: Framework for peak two-foot vertical jump optimization. All factors need to maximize the takeoff velocity and reduce angular rotation of the COM by having the line of force application directed through the COM. Improving these variables would improve the vertical jump height (Vertical COM displacement). The varying line types are to highlight the various interactions amongst the factors.

2. Review of the Relevant Literature - Variables that Influence Vertical COM Displacement

2.1. Take-Off Velocity

For the purpose of this thesis, displacement of the COM in the vertical axis will be difference between the peak vertical position during flight and the vertical COM position at take-off; this will be used to define vertical jump performance. To determine this vertical COM displacement multiple methods can be applied. These methods include: 1) time in the air, 2) impulse-momentum, and 3) work-energy (Linthorne, 2001; Moir, 2008). These methods determine the vertical displacement from knowledge of the vertical velocity at the instant of take-off. The COM displacement may be obtained from the take-off velocity (TOV), by applying the law of conservation of mechanical energy to the flight phase of a jump.

During a vertical jump the effects of air resistance may be considered insignificant, and thus the jumper can be viewed as a projectile in free flight (Linthorne, 2001). As a projectile, any change in potential energy will cause a corresponding change in kinetic energy. If we take the time points of TOV and peak jump height, the following set of relationships will provide the relative vertical COM displacement:

$$½\, mv^2_{TO} + mgh_{TO} = ½\, mv^2_{peak} + mgh_{peak} \qquad (1)$$

Where m = mass of the jumper, v = velocity, g = acceleration due to gravity, h = vertical COM position, TO = time of takeoff position, peak = time of peak vertical COM position

$$\textit{Vertical COM displacement (Jump height)} = hpeak - hTO = V^2_{TO}/2g \qquad (2)$$

Where vertical velocity at peak of the jump is zero ($v_{peak} = 0$).

Since, it is apparent that the magnitude of the TOV has a large effect on the vertical COM displacement, it is essential that this be maximized to achieve the greatest COM movement.

2.2. Line of Force Application

As important as the take-off velocity is to the vertical jump height, it can be limited by direction of the ground reaction force (GRF). The line of the GRF must be directed through the COM at the moment of take-off, to minimize any production of angular impulse. Generation of angular impulse reduces the ability to achieve maximum vertical TOV, because a larger horizontal TOV may be obtained (McGill, 2009).

In certain tasks an angular impulse may be required to project the COM in the anterior-posterior, medial-lateral or combination of these axes. For example, a volleyball player aiming to spike the ball may require forward translation of the COM and thus a direction of the GRF through the COM would not be optimal. Beyond task-related instances there is the ongoing control of balance, by which the COM is maintained within the base of support (BOS). This ongoing control is seen when the COM is outside the base of support and a correction is made by producing an angular impulse to move the COM within the BOS to maintain balance.

2.3. Motor Control – Planning and Execution

When determining the characteristics of a skilled or non-skilled performer of any movement task or behaviour, differences in the anthropometry and muscle physiology are likely present. However, even if the optimal physical characteristics are present, the muscles and body segments must still be appropriately controlled. This control is created and executed by a motor strategy developed by the CNS that determines the type of muscle to be recruited and its associated onset of recruitment/de-recruitment, duration, rate and amplitude. The result of this executed motor strategy is the movement of body segments to ultimately perform the desired movement. Since, the motor strategy has a critical role in the outcome of voluntary movement; it would certainly have an influence on the performance of a multiple joint movement task such as vertical jumping. Relevant to this thesis are not the different motor control strategies, but rather the mechanical output of these various motor strategies used to perform a vertical jump. Focusing on the amount of work done at each lower limb joint, would reflect the motor plan’s desired contribution of each joint in performing the jump. This area will be the focus of this thesis and will be discussed in greater detail in a later section, but the following few sections will document other contributors (shown in Figure 1) to vertical jump performance.

2.4. Anthropometry

An individual’s structural design both skeletal and muscle, will have implications for force production and overall movement performance. Specifically for vertical jumping, a number of anthropometric factors have been investigated, as to the relationship between the anthropometric variable and jump performance. It has been found that variables such as: body fat percentage, height, leg length and muscle girth have had significant associations with vertical jump performance.

Body fat percentage has been previously investigated to determine its relationship with vertical jumping. A study by Davis et al (2003) demonstrated a significant negative relationship between body fat percentage and vertical jump height after measuring twenty-three male recreational athletes. These results were confirmed by Ostojic et al (2006), after 60 professional basketball players were evaluated through multiple anthropometric variables including percent body fat. Unfortunately, these studies did not discuss any potential mechanisms that are involved for this relationship, but it is likely that additional body fat is associated with higher body mass (Ostojic et al., 2006). With the increased body mass the jumper is required to generate a linear impulse that is larger than the impulse created by body weight.

Height appears to be another anthropometric variable that has a relationship with vertical jump performance (Ostojic et al., 2006; Sheppard et al., 2008). In the same study by Ostojic et al (2006), the height of a player had a strong negative correlation with vertical jump height. Using the results from this study, this relationship could be attributed to the strong positive relationship between height and body fat percentage. Another mechanism to explain this relationship between height and vertical jump performance may include nerve conduction velocity. A study by Bodofsky et al. (2009) examined the ulnar nerve from below the elbow to the wrist and found that the square root of its length was inversely proportional to the conduction velocity. This suggests that the propagation of action potentials along a lengthier axon would be reduced, and thus rate of muscle recruitment could suffer.

Though an increase in height may have adverse effects on jump height, longer lower limbs could offer advantages to a jumper by which he or she would be enabled to accelerate over a greater distance, reducing the demand for high rates of contraction to accelerate themselves to a given speed. The lower contraction rates would allow higher forces to be developed and more work done on the COM (Alexander, 1995).

Finally, the size of a muscle may have implications to force production and vertical jump performance. A larger physiologic cross-sectional area (PCA) may reflect an increased number of sarcomeres present. This could result in a greater number of cross-bridge formations, which would increase force production. In the case of vertical jumping, larger muscle size for all prime movers may be positively associated with performance. In the study by Davis et al (2003), the authors measured thigh girth and calf girth, and found that as calf girth increased so did jumping performance. Unfortunately, this study utilized recreational athletes and not a subject pool of elite athletes. However, it does demonstrate a link between muscle girth and jumping performance.

2.5. Muscle Physiology

The previous section documented a few anthropometric parameters related to vertical jump performance. Another factor that appears to influence jumping performance is muscle physiology. Specifically, this section will discuss muscle fibre types and its contribution to speed, force and power. In regard to fibre types there appears to be two categories, type I and type II (Eberstein and Goodgold, 1968).

One of the major differences between these two fibres types is the means by which ATP is obtained and utilized. Type I fibres have higher mitochondrial density and myoglobin content than type II fibres which increases its capacity for aerobic metabolism. Conversely, in type II fibres there are higher amounts of phosphocreatine and glycogen stores, and glycolitic enzymes increasing its capacity for anaerobic metabolism (Powers and Howley, 2004). Anaerobic metabolism is favourable for conditions where the rate of ATP utilization is high, whereas the opposite is true for aerobic metabolism. Therefore, if increases in contraction velocity are required then obtaining ATP through anaerobic metabolism is more efficient in responding to high rate of ATP demand. This is an example of one method by which fibre type affects the rate of cross-bridge formation. An additional mechanism to increase the rate of cross-bridge formation in type II fibres is to minimize the time duration of calcium (Ca^{2+}) release (Fox et al., 1993). The release of Ca^{2+} allows facilitation of the thin filament, providing the thick filament a binding site. Therefore, the faster the release, the quicker the facilitation and binding by the thick filament.

Fibre type also influences the rate of relaxation, which may be important for those movements where maximum joint speed is required. Consider that an initial contraction is required to generate joint movement, but if the contraction is sustained or the amplitude increases there would be accompanying stiffness slowing joint motion and reducing speed (McGill et al., 2010). Therefore the faster the muscle relaxes after an initial contraction, the faster the joint speed. Type II fibres have higher rates of relaxation, which is a result of having greater volume of sarcoplasmic reticulum Ca^{2+}-ATPase (SERCA) pumps than type I fibres. More specifically, type II fibres consist of primarily the SERCA1a isoform, whereas type I fibres are mainly composed of the SERCA2a isoform (Tupling, 2009). The SERCA1a isoform has been shown to have higher Ca^{2+} transient kinetics than the SERCA2a isoform (Sumbilla, 1999).

Another difference between the two fibre types is the diameter. Type II fibres have larger diameters than type I fibres. This allows type II fibres to have more protein contractile filaments, increasing the number of possible cross-bridge sites. Once the number of potential cross-bridge sites increase, the ability to generate a higher muscle force increases (through more actin-myosin interaction).

Optimization of rate and amplitude of contraction has a direct effect on the muscle power capabilities. This would affect the power development at the joint having further implications on the peak power and work done on the COM. Since, the peak power is strong predictor of vertical jump performance (Aragon-Vargas and Gross, 1997), it is also likely that performance is also related to the amount of type II fibres in a muscle. Bosco and Komi (1979) attempted to seek this relationship and found using muscle biopsies in the vastus lateralis muscle that the percentage of fast twitch fibres was significantly related jump height.

It is clear that certain fibre types may be more predisposed than others in affecting muscle power development, by higher rates and amplitude of contraction. This along with the literature demonstrates the likely importance muscle function and physiology has to jumping performance.

2.6. Storage and Recovery of Elastic Potential Energy

Elastic potential energy is potential stored as a result of deformation of an elastic object such as a spring. In the human body, this elastic potential energy is likely stored in muscle and tendon. By recovering this stored energy during movement, it can reduce metabolic cost by conserving energy. The storage and recovery of elastic potential energy is a mechanism used to explain how the human body economizes energy use, but is also the mechanism to explain the added performance from the pre-stretch of a muscle. More specifically in jumping, it is clear that the added pre-stretch of leg extensor muscles through an initial countermovement, can result in higher jump heights than if the jump started from a squatted position (Komi and Bosco, 1978; Bobbert et al., 1996; Vanezis and Lees, 2005). This pre-stretch has been largely explained by the storage and recovery of elastic energy that primarily takes place at the tendons. Due to the viscoelasticity of a tendon (Arnold, 1974 as cited by Van Ingen Schenau, 1984), any stored elastic energy may be quickly lost to heat and should thus be immediately recovered to avoid energy loss through concentric action of the muscle. The CNS has a major responsibility in ensuring the appropriate timing of muscle recruitment. If the muscle shortens too soon the tendon may have not deformed enough to store elastic energy that could affect performance, and if the muscle shortens too late it risks recovering most of the stored elastic energy. The muscle composition may also be a contributing factor to the recovery of elastic energy. It has been demonstrated that the recovery of elastic energy increases with a corresponding increase in the percentage of type II fibres during slow stretching speeds and long coupling times (Bosco et al., 1986).

An alternative hypothesis was presented by Van Ingen Schenau (1984), where he claims that the added effect to energy economy and additional force from a pre-stretch is not largely due to the storage and recovery of elastic energy. The effect of pre-stretch may be due to having more available sites for cross-bridge formation at reduced metabolic cost. If a pre-stretch did not take place (as is the case in a squat jump), the number of available sites for muscle shortening is reduced because cross bridges are already formed.

It may be that the storage and recovery of elastic energy due to deformation of the tendon, and the increased capacity of cross-bridge formation from an initial pre-stretch are both occurring. These mechanisms must be understood, as they do have an added effect on jumping performance.

2.7. Spine Stability

As previously mentioned one of the control challenges the CNS faces is to maintain joint stability, while still allowing for the necessary joint moment development. The lumbar spine consists of 5 vertebrae articulated together and experience compressive and shear forces during static and dynamic movement. These forces could perturb these joints in a way that they do not return to its original state or equilibrium. In vertical jumping the compressive load at the lumbar spine are likely high due to required ground reaction forces necessary to overcome one's body weight. Therefore, the likelihood of joint instability is higher.

To prevent instability the CNS recruits muscle, this increases the compressive forces and resists motion in its axis (McGill, 2002). As the muscle generates higher tension it further resists motion, as is the case when a spring has a higher stiffness, it provides greater resistance to change its length. However, a single contracted muscle acting on a lumbar spine joint would not be beneficial because it can rotate in three planes and translate along three axes (McGill, 2002). Therefore, trunk muscles must create a stable equilibrium in all the planes and axes. The CNS must coordinate recruitment (both in timing and amplitude) of the trunk muscles to meet the demands imposed on the lumbar spine. If recruitment is optimized it can increase the resistance (or stiffness) of a lumbar spine joint to perturbation in any plane or axis.

In terms of performance and jumping, a lumbar spine more resistant to perturbation (i.e. stable lumbar spine) should allow for improved transfer of energy from the upper and lower bodies, because it minimizes dissipation. A compliant spine would absorb energy generated from the hips and arms, and this would effectively decrease the total mechanical work done on the COM, and therefore affect its vertical displacement. It would then appear that making the lumbar spine completely resistant to any joint motion would possibly optimize transfer of energy and lower limb joint mechanics, but this would also increase metabolic cost (due to increased levels of muscle recruitment) and eliminates any ability for back extensors to contribute to jumping performance.

Therefore, some level of lumbar spine stability is critical in preventing injuries (McGill, 2009) to passive tissues and allowing for transfer of energy between upper and lower body segments.

2.8. Importance of Strategy

The understanding of how anthropometry and muscle physiology influence vertical jump height is critical for developing training methods and exercises that enhance its performance. However, improvement with these factors from physical training may be limited because of its large dependence on genetics.

As mentioned in an earlier section the motor plan/strategy is responsible for coordinating muscle recruitment to ultimately develop joint moments and create movement. This makes strategy an important factor for further investigation into its role in vertical jump performance.

There has been investigation into the muscle recruitment patterns associated (reflecting motor strategy) with vertical jumping separate from any performance measure. These patterns have been identified using electromyography (EMG). EMG is a time-varying signal that can be used as a tool to provide temporal and amplitude information on the recruitment of an observed muscle. Temporal information may include the onset, duration and rate of recruitment, whereas amplitude knowledge would describe the total activity of the recruited muscle. Additionally, EMG can also be used to describe the force outputs of a muscle through linear enveloping. Linear enveloping corrects the electromechanical delay present between the electrical action potential delivered to the muscle and force output to the segment via the tendon. However, linear enveloped EMG is typically stripped of high frequencies, thus making it limited in providing temporal information. Regardless, EMG has been used in studies (Bobbert et al., 1988; Pandy and Zajac, 1991; Rodacki et al., 2002) to reflect the underlying motor control of the vertical jump movement. For example, a study by Bobbert et al. 1988, looked into the muscle recruitment patterns of countermovement vertical jumping during the ascent phase, in an attempt to define how the CNS coordinates multiple joints and segments. These authors found that muscles attained peak recruitment in order from proximal to distal at the time of joint reversal, starting with the hip extensors (hamstrings group and gluteus maximus) followed by the knee and ankle extensors. The study also revealed that the possible role for bi-articular muscles in jumping is to transport energy from proximal to distal joints, and allow for mono-articular muscles to fully shorten without risking damage to the joints. Unfortunately it is difficult to know whether the described muscle recruitment patterns are reflective of single jumps, because these muscle recruitment patterns were achieved by averaging signals across trials and subjects.

Since this study there has been a lack of research in determining a motor strategy for the vertical jumping movement with EMG analysis alone. This may be due to the fact that using EMG alone to define the motor strategy can be difficult, because of the large variability that is present from person-to-person. It may be better suited to characterize the motor strategy, first through the analysis of mechanical outputs, and then utilize EMG to reflect the underlying control of the mechanics.

Previous studies have used joint kinetics to examine the mechanical strategy of vertical jumping, but the results have been conflicting. These studies have probed the lower limb joints to view their contribution to two-foot vertical jumping. Hubley and Wells (1983) had participants perform both CMJ and SJ without arm swing and found the relative joint contribution to the total work done on the COM. Their results revealed that the greatest contributor to the total work done was the knee (49%), followed by the hip (28%) and ankle (23%). The aim of the study was not to determine whether these joint contributions were related to performance, but was rather to understand the movement. This study was not without limitations as there was a small sample of jumpers (n=6). The joint work contributions were averaged across subjects, and due to the large variability from subject to subject, the reported data is not truly reflective of individual subjects. Finally, although the study's aim was not to relate their findings to performance, the subject pool used was not regarded to be familiar with the task and would be a poor sample selection if the aim were different. Fukashiro and Komi (1987) performed a similar study but only analyzed joint contributions within one person. This would eliminate any variability created by inherent anthropometric and muscle physiology differences that occurs when comparing between subjects. Their findings were conflicting to the Hubley and Wells (1983) data set, as the major contributor to the total work done was the hip (51%) followed by the knee (33%) and the ankle (16%). This may suggest that the vertical jump movement can be performed with a strategy that results in either hip or knee dominance. However, the aforementioned studies do not aim to relate these findings to performance, and thus it is uncertain the influence these strategies could have on jumping performance.

Vanezis and Lees (2005) aimed to quantify certain kinematic and kinetic variables for good and poor performers of a two-foot vertical jump. The authors found that good jumpers exhibited significantly higher ankle work done than poor jumpers. In contrast, the hip or knee work done was not significantly different between the two groups. Further examination revealed that there was large between subject variability present in the hip and knee data, which may have limited the ability to detect differences. As noted by Vanezis and Lees, participants could vary by inherent differences in their anthropometry and muscle physiology, and this could have heavily influenced their jumping performance. Therefore, the performance of the good jumpers could have less to do with the control of the individual joints and more to do with inherent biological differences.

A study by Aragon-Vargas and Gross (1997) evaluated segmental kinematic and kinetic variables within a subject to eliminate any genetic and structural influence. Eight jumpers performed nearly 50 two-foot maximum countermovement jumps without arm swing. Three of eight jumpers were selected based on their vertical jump height to represent the Best (B), Worst (W) and Average (A) jumpers. A multiple-regression analysis containing a number of different variables was applied to the three jumpers to determine the optimal model of variables. It was found that peak hip power was the single most important variable in predicting performance (accounting for 37% of the explained variance). Interestingly, peak knee power was not a factor in any of the best predicted models for jump height. However, this does not mean that its relative contribution to the total mechanical peak power of the COM is not important. In fact, after further post-hoc calculations were done it was found that the knee had a higher contribution of peak power than the hip in both the best and worst jumpers. In addition, the relative contributions of peak power in the worst jumper (27% hip and 32% knee) were similar to the best jumper (24% hip and 36%), which may suggest that magnitude of the peak power is also important.

From the early studies (Hubley and Wells, 1983; Fukashiro and Komi, 1987) that characterized the contribution of the lower limb joints to vertical jumping, conflict in the data existed for the joint that was the major contributor. The study by Vanezis and Lees (2005), attempted to characterize good and poor jumpers by evaluating joint work and powers, but failed to reveal any significant differences with the hip and knee. When looking at peak power, it appears that peak hip power is a significant contributor to vertical jump height, but when compared to peak knee power its relative contribution to the total peak power (from the hip, knee and ankle) is lower (Aragon-Vargas and Gross, 1997). It therefore seems important to address whether the changes in mechanical contribution between hip and knee have any association with vertical jump height.

If changes in mechanical contribution between the hip and knee do have an association with jump height, then it does have implications for training. In the case of improving storage and recovery of elastic energy, exercises aiming to optimize this variable could be improved in design to fit the hip and knee relationship. For example, if it is found that vertical jump performance increases with a higher hip than knee contribution, exercises to improve storage and recovery of elastic energy should be designed to utilize more hip. In light of the potential importance, this study will investigate whether changes in the hip or knee mechanics influence vertical jump performance.

3. Research Questions and Hypotheses

It is proposed that strategies that exhibit a single-joint's dominance would positively influence jumping performance; therefore the primary objective was to determine whether a greater hip or knee contribution influences vertical jump height. This is being investigated by evaluating a jumper's preferred strategy and two trained strategies that encourage hip and knee mechanical dominance. Evaluation of the preferred jumping task will involve between subject analyses, whereas the probing of the hip and knee-dominant tasks will involve analyses performed within subject. The secondary objective was to determine possible relationships between the joint mechanics of a vertical jump and the activity of specific muscles (mono and bi-articular) that act at the joint. To address this goal, all three jumping tasks will be investigated. Finally, the third objective was to explore the coupling between the lumbar spine and hip. Specifically, we are looking to determine whether changes in the lumbar spine kinematics influence the hip kinematics. The following sub-sections describe specific hypotheses to address the research objectives introduced above.

3.1. Hypothesis #1

Across Subjects:	It was hypothesized that a higher hip than knee contribution (represented by hip/knee work ratio) would positively relate to an increase in the vertical COM displacement during the preferred jumping task.
Within Subject:	Comparisons of the hip and knee dominant jumping tasks will show a higher vertical COM displacement in the hip dominant task.

3.2. Hypothesis #2

Across Subjects: The mono-articular gluteus maximus (GMax) will have a greater contribution than the bi-articular biceps femoris (BFem) as hip work and peak power increase.

The peak activity and peak rate of activation will be used to test these hypotheses.

Within Subject: The ratio of GMax/BFem activity will be higher in the hip compared to the knee-dominant task.

3.3. Hypothesis #3

Across Subjects: Hip joint velocity will increase with a decrease in lumbar spine velocity.

4. Methodology

4.1. Participants

Twenty male participants with an average age, height and body mass of 21.0 ± 2.0 years, 1.90 ± 0.08 m, and 86.30 ± 8.37 kg respectively, participated in this study. Ten of the participants were active varsity basketball players, 8 were active volleyball players, 1 was an active long jumper, and 1 participant was a recreational athlete. All participants were free of knee or hip pain. All participant recruitment and data collection procedures were performed in accordance with the University of Waterloo's Office of Research and Ethics guidelines.

4.2. Instrumentation

The instruments being used to address the primary research questions include electromyography, three-dimensional kinematic data and force platforms.

4.2.1. 3-D Kinematic/Kinetic Model

The three dimensional kinematic model was collected and created using Vicon Motion Systems. This system required an initial calibration of the system before use. The calibration consisted of three steps: 1) Aim the Vicon MX Cameras at the 5 marker calibration wand, 2) calibrate the cameras to the movement of the 5 marker wand, and 3) apply the origin (0,0,0) to the research space. The Vicon MX Cameras captured the markers at a sampling rate of 200 Hz.

After the calibration of the 8 Vicon MX Cameras, 55 passive optical markers were applied to the participant. Twenty-two of the markers were strictly for calibration of the subject to a pre-created template, which were later removed during the collection of jumping tasks. The remaining thirty-three markers were present during the jumping tasks for the tracking of segments such as the trunk, pelvis, thigh, shank and foot. The tracking markers were on rigid plates to reduce the risk of skin movement artifact; they were attached to body segments by adhesive spray, double-sided carpet tape and a strap.

A summary of all the markers that were placed on the participant's body are listed in Table 1.

Table 1: Summary of passive optical markers

Segment/Joint	# of Markers	Location	Tracking or Calibration
Right & Left Foot	5 per foot	1st and 5th metatarsal heads, top of foot, navicular, heel	Tracking (1st & 5th metatarsal heads were also used for calibration)
Right & Left Ankle	2 per ankle	Medial and lateral malleoli	Calibration
Right & Left Shank	4 per shank	Lateral side of shank	Tracking
Right & Left Knee	2 per knee	Medial and lateral femoral condyles	Calibration
Right & Left Thigh	4 per thigh	Lateral side of thigh	Tracking
Right & Left Hip	1 per hip	Greater trochanter	Calibration
Pelvis	6	Right & Left ASIS, PSIS and Iliac crests	Calibration
Sacrum	4	Caudal to PSIS on sacrum	Tracking
Thorax	4	At level of 12th thoracic vertebrae	Tracking
Right & Left Acromion	2	Acromion process	Calibration
C7	1	Spinous process	Tracking
Sternum	1	Sternal notch	Tracking
Right Scapula	1	Middle of scapular body	Calibration

4.2.2. Kinetic Data

Ground reaction forces were collected from two (AMTI Biomechanics) force platforms. Participants had a foot on each force plate. Symmetry was assumed between both legs, but jumping off of one plate would have constrained the participant's preferred stance width. Therefore, two force plates were collected to address this issue. To time synchronize the force plate and kinematic data, it was sampled at 2400Hz.

4.2.3. Electromyography

Before any application of Ag-AgCl electrode pairs, the skin was prepared to reduce impedance to a range of 0-10 kohms between the skin and the electrode. This was achieved by removing dead skin cells with a skin exfoliate (NuPrep) and the area cleansed using a 50/50 H_20 and ethanol solution. Removal of hair with a razor blade only occurred when the impedance was over 10 kohms. The value of the impedance was measured using a standard impedance meter. The collected EMG signals were initially amplified (Octopus AMT-8) and then A/D converted with a 16-bit, 64 channel analog to digital (A/D) converter at 2400Hz.

Sixteen surface electrode pairs were placed bilaterally with an interelectrode distance of approximately 2.5 cm on the following muscles: right and left rectus femoris (RRFem and LRFem), vastus lateralis (RVLat and LVLat), gluteus maximus (RGMax and LGMax), biceps femoris (RBFem and LBFem), gastrocnemius (RGas and LGas), external oblique (REO and LEO), internal oblique (RIO and LIO), right rectus abdominis (RRA) and right upper erector spinae (RUES).

Each participant was required to perform a maximum voluntary contraction (MVC) of each measured muscle for normalization of each channel for three repetitions; each repetition was separated apart to allow for enough rest time that was determined by the participant. Detailed electrode placement and MVC protocols are summarized in Table 2.

Table 2: Summary of EMG electrode placement and MVC protocols

Muscle	EMG Location	MVC Protocol
Right & Left GMax	Middle of muscle belly approx 3cm lateral to gluteal fold	Subject lies prone with knee flexed at 90^o, hip extension is resisted
Right & Left BFem	Muscle belly midway between knee and hip on posterior thigh	Lying supine, instructed to flex knee and extend hip while being resisted
Right & Left RFem	Muscle belly midway between knee and hip on anterior thigh	Seated position with resisted knee extension and hip flexion
Right & Left VLat	Medial to iliotibial tract and superior to patella	Seated position with resisted knee extension
Right & Left Gas (Med Head)	Muscle belly superior to the soleus	Resisted standing plantarflexion
Right & Left EO	Approx. 3 cm lateral to linea semi lunaris	Sit up position and subject is manually braced by researcher while producing lateral bend and twist moments
Right & Left IO	Caudal to external oblique electrodes, superior to inguinal ligament	Sit up position and subject is manually braced by researcher while producing lateral bend and twist moments
Right RA	Lateral to the navel	Sit up position and subject is manually braced by researcher while producing a trunk flexor moment
Right UES	Approx. 5 cm lateral to the spinous process at T9	Resisted maximal extension in Biering-Sorensen position

4.3. Jumping Tasks

Participants were required to perform a two-foot maximal countermovement jump (CMJ) with arm swing. A CMJ was performed by an initial downward movement followed by an immediate rise up. The use of a CMJ with arm swing was more reflective of jumping behaviour in sporting activities, as opposed to performing a jump without the initial downward movement or restricted arm use.

For all jumps participants were able to self select the amplitude of the countermovement (initial lower of COM) prior to jumping. Participants performed 30 jumps with at least a minute rest between jump trials to reduce any effect of fatigue on performance. Ten of their jumps were executed using their preferred jump, and the remaining 20 were manipulated to encourage hip and knee dominance.

Prior to the onset of each jumping trial participants were instructed to set their feet in their preferred stance width, which was marked with adhesive weather-stripping before the start of collection. They were then instructed to stand relaxed with no movement and on the cue of the researcher perform their maximal jump. There was no specified target that they were required to land on, but the aim was to land somewhere on the two force platforms they had jumped from. In between trials participants were allowed to sit on a stool, which was removed during the jump trial.

4.3.1. Jump Task Training

After participants perform ten repetitions of their preferred jump they underwent two ten minute sessions whereby the researcher manipulated their jumping method to encourage either hip or knee-dominance. The order of hip or knee manipulation experienced by the participant was randomized to account for any possible order effect; participants experienced both manipulations. Once the participant finished the 10 minute coaching session, they performed 10 maximal jump trials in the way they were just instructed.

4.3.1.1. Hip-Dominant Task

To enhance the hip work done, a few things required training: gluteus maximus recruitment, squatting patterns and jumping.

Extension of the hip is the result of recruitment from the hamstrings muscle group and gluteus maximus. However, the hamstrings are bi-articular and are also recruited to flex the knee. Its ability to extend to the hip is limited, and thus the importance of the gluteus maximus to create hip extensor torque is likely greater. The first step in altering the participant's mechanical strategy to emphasize increased hip work was to ensure that the gluteus maximus could be recruited during hip extension. The participant was instructed to lie supine with their knees flexed to 90^o and feet flat on the floor (Figure 2). On cue the participant raised their hips into a bridge. The hamstrings tendons were palpated by the researcher to provide feedback to the participant regarding the involvement of the hamstrings. The goal of the participant was to perform hip extension with little to no palpable tension in the hamstrings. Please note that the pelvis rigid plate of markers was removed, because the participant was lying supine. Failure to remove the markers would have been uncomfortable to the participant and cause damage to the markers; great caution was exercised when reapplying the plate after the bridges were complete.

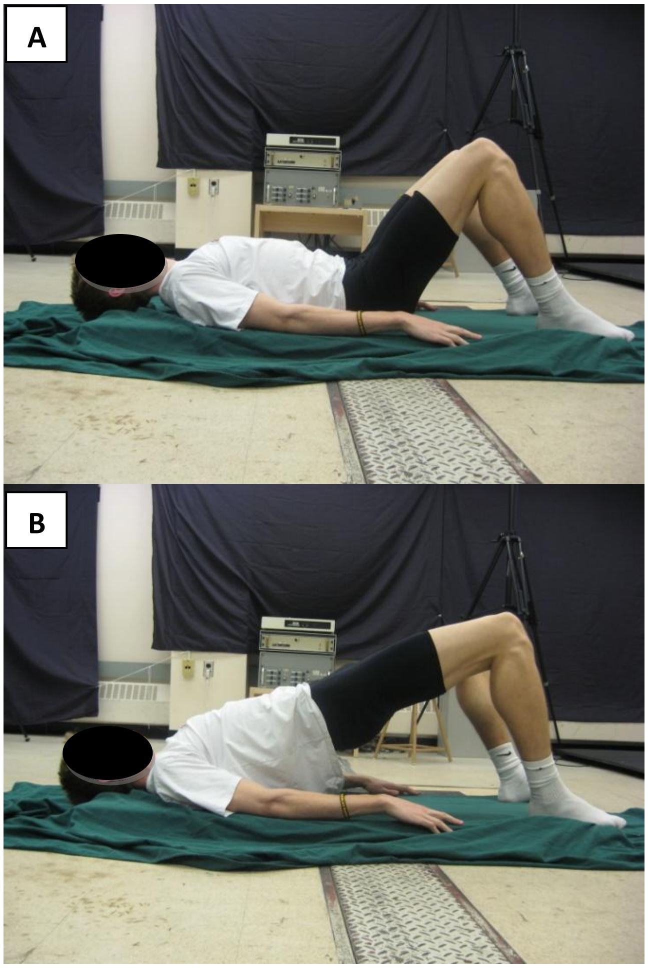

Figure 2: (A) Subject lying prone with knees flexed at 90^{o}, and (B) extending at the hip through gluteal activation.

The second step taught the participant a squatting pattern that limited anterior translation of the knee joint in the descent and ascent of the COM (Figure 3). The participant had a resistance band around their knees (stiffness = 1.02 N/cm), which forced their hip joint into internal rotation (pushing the knees together in the frontal plane). Therefore, the participant was cued to externally rotate at the hip, spreading the knees apart. The addition of the band has been shown to increase Gluteus Maximus recruitment, because of the muscle's additional involvement in external hip rotation. Squats were completed until the subject was able to attain the required motion; therefore the number of squats was documented but not controlled.

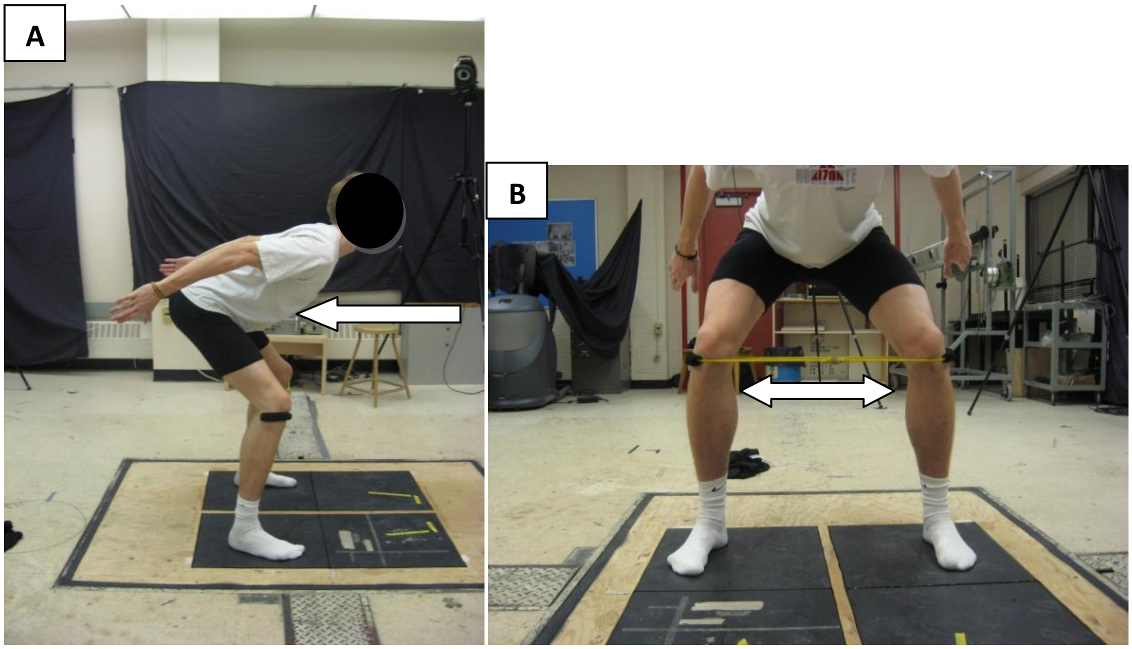

Figure 3: (A) Subject squatting with band around knees limiting the anterior translation of knees, (B) Frontal view of band around knees.

The final step required performing jumps (sub-maximal and maximal) from the learned squatting pattern involving the resistance band. The researcher cued the participant to limit anterior translation of the knee joints during both descent and ascent of the COM. The resistance band was moved from the knees to the ankles to avoid interference during the jumping movement (Figure 4). A progression from sub-maximal to maximal jumps was implemented, but the number of jumps varying across subjects depended on the rate they learned the task; the number of sub-maximal and maximal jumps were documented.

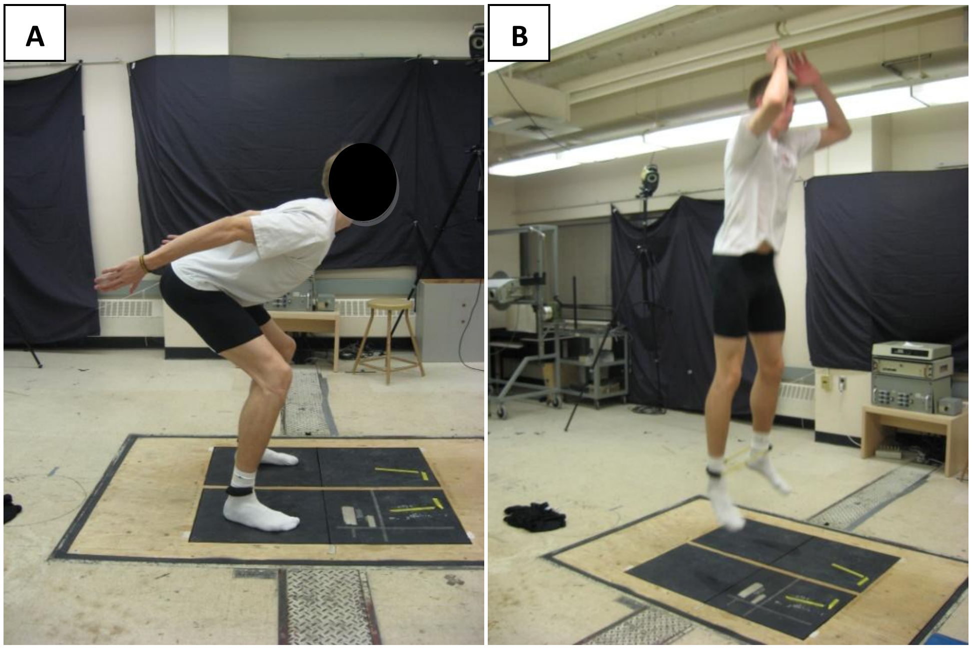

Figure 4: (A) Countermovement performed with band at ankles, (B) Participant jumps while attempting to keep the band spread apart.

4.3.1.2. Knee-Dominant Task

Training to increase the knee work involved: squatting patterns and jumping. The first step required the participant to perform squatting patterns that results in anterior translation of the knee during the descent of the COM (Figure 5). The participant squatted by flexing through the knees, and having them meet a string that was in front of the toes.

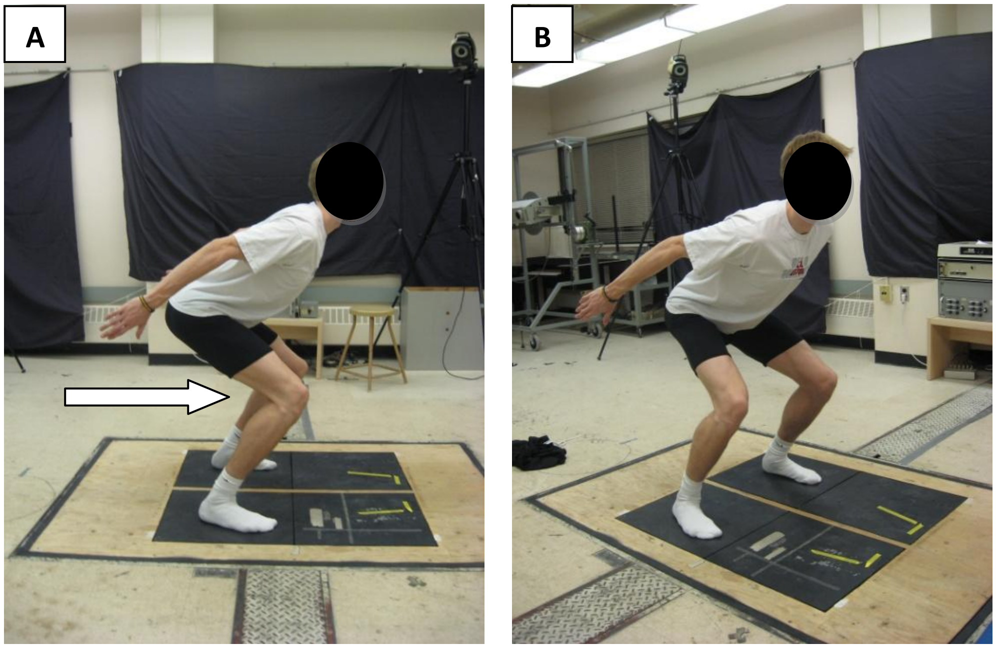

Figure 5: (A) Participant squats with knees flexed and translated anteriorly over toes, (B) Sagittal-frontal view of the participant squatting.

The second step had the participant performing jumps using the learned squatting patterns. The researcher cued the participant to ensure anterior translation of the knee joints during the initial ascent of the COM. After either the hip or knee manipulation, the participant rested 5 minutes prior to performing the 10 jump trials.

4.4. *Summary of Experiment Protocol*

Below is a graphical summary of the experimental protocol (Figure 6). The protocol begins with the EMG electrode preparation and application and ends with the performing the of hip and knee dominant jumping tasks.

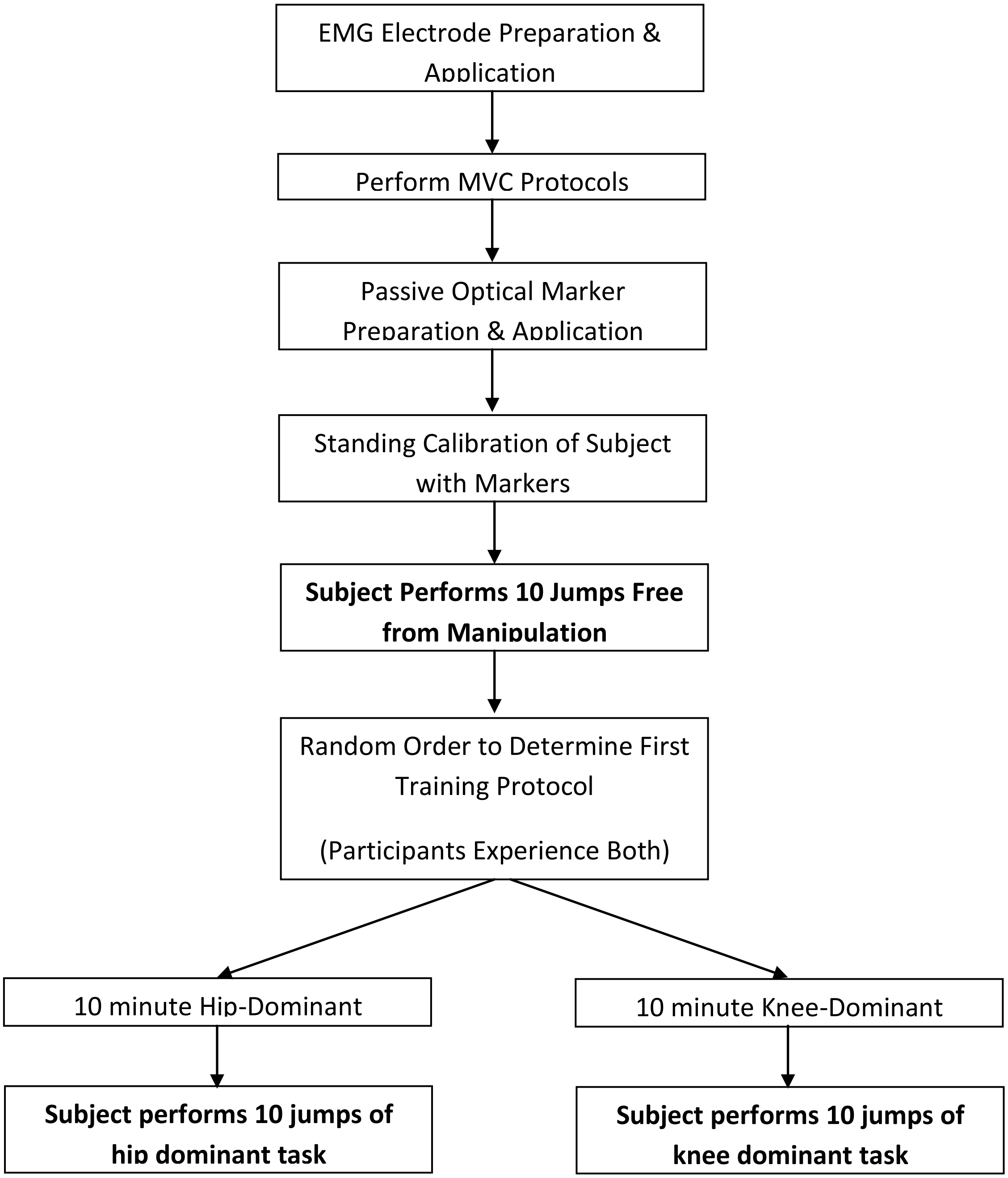

Figure 6: Graphical summary of experimental protocol

4.5. Data Analysis

All kinematic marker data was low and dual-pass filtered with a second-order Butterworth filter and cut-off frequency of 6 Hz. The analog force plate signal was calibrated using pre-defined calibration matrices, and later conditioned with a low and dual-pass fourth-order (D'Andrea et al., 2005) Butterworth digital filter, and cut-off frequency set at 75 Hz (determined using residual analysis).

Using the ground reaction force in the vertical direction, key events such as "Onset of Movement" and "Takeoff" were marked. The onset of movement was marked at the point where the vertical force rises above or below a pre-defined threshold. The takeoff was determined at the moment when the participant left the force platform; this was when the vertical force was closest to 0 N. The time from onset to takeoff was used to determine the vertical COM displacement.

The remaining critical event was the time point where eccentric muscle action switches to a concentric contraction (i.e. start of propulsion); this was determinable using the linear vertical impulse. After onset, when the linear vertical impulse reached zero, the time point was marked as "Zero Velocity" to identify the start of propulsion. The time from zero velocity to takeoff was the area of interest (called "propulsion phase") to determine the max force (vertical direction), rate of force development (RFD), rate of force relaxation (RFR), work done, peak power and muscle activity parameters.

The max force was determined as the highest vertical ground reaction force within the propulsion phase. The peak RFD and RFR were determined from the derivative of the vertical ground reaction force signal. The peak RFD was the maximum value of the derived signal between zero velocity and the time point of max force, whereas the peak RFR was the minimum value of the derived signal between max force and the time point of takeoff.

The EMG signals were filtered using a dual-pass bandpass second-order Butterworth filter with a low end cut-off frequency of 30 Hz to remove any possible jump movement artifact and biologically inherent noise, such as electrocardiography (Drake and Callaghan, 2006) and a high end cut-off frequency of 500 Hz. The raw signals were corrected for bias and then full-wave rectified. Finally, EMG signals were integrated (IEMG) between zero velocity and takeoff to determine a muscle's total activity, this was used to address any within subject questions. For between subject analyses, EMG was linear enveloped using a second-order low-pass single pass Butterworth filter with a cut-off frequency of 3 Hz, and normalized to the peak amplitude of a maximum voluntary contraction. The peak muscle activity was determined within the propulsion phase as the maximum value of the linear enveloped signal, and the peak rate of activation was the maximum slope within the same time frame. To gauge the dispersion of the peaks for certain muscles, a time range (measured in seconds) was computed between the first peak and last peak; this variable will be identified as the "range".

All inverse dynamic calculations that determine the necessary joint powers and work done values were performed in the Visual 3D software (C-Motion Inc., Kingston, ON, Canada). Vertical COM displacement and muscle activity amplitudes were determined using custom developed programs using Labview software (National Instruments Corp., Austin, TX, USA).

There were instances of poor kinematics or EMG signals that would have contaminated the results had they been left in, therefore these cases were removed from the data set. For example, the kinematics of the hip and knee jumping tasks for one participant were not correct and may have been the result of movement in the rigid body plates and/or errors in the reconstruction of the kinematic markers. This would affect the resultant kinetic model and thus their kinematics, joint work and power data were not included in the results.

4.6. Statistical Analyses

All variables analyzed were screened for normality by evaluating normal distribution plots, statistical tests for normality, skewness and kurtosis. For analyses involving the comparison of means both a paired-samples t-test (parametric data) and Wilcoxon signed-rank test (non-parametric data) were used. To establish any associations between variables both the Pearson product-moment correlation (parametric) and Spearman rank correlation (non-parametric) coefficients were used. Directional hypotheses that were made apriori used one-tail significance, whereas non-directional hypotheses or in cases where the direction of apriori predictions were incorrect two-tailed significance was applied. All statistical tests were performed using SAS 9.2 (SAS Institute., Cary, NC, USA).

Our statistical outputs for the results were defined in the following manner:

(m(aa) = bbb, p = xxxx), where *m* = test statistic (*m* could be defined as r = correlation coefficient, t = t-test, S = Wilcoxon test)
aa = degrees of freedom
bbb = test value
p = probability
xxxx = probability value

5. Results

From the ten trials that were available for analysis only the last 5 were used; this was done for two reasons. First, a few subjects reported a lack of warm-up affected the jump heights of their first few repetitions, and second learning could have continued to occur in the hip and knee-dominant jumping tasks. These concerns for learning were confirmed by reviewing the trial to trial performance. Below is an example of a participant demonstrating jump heights increasing for the first few repetitions and then starting to stabilize near the last 5 (Figure 7).

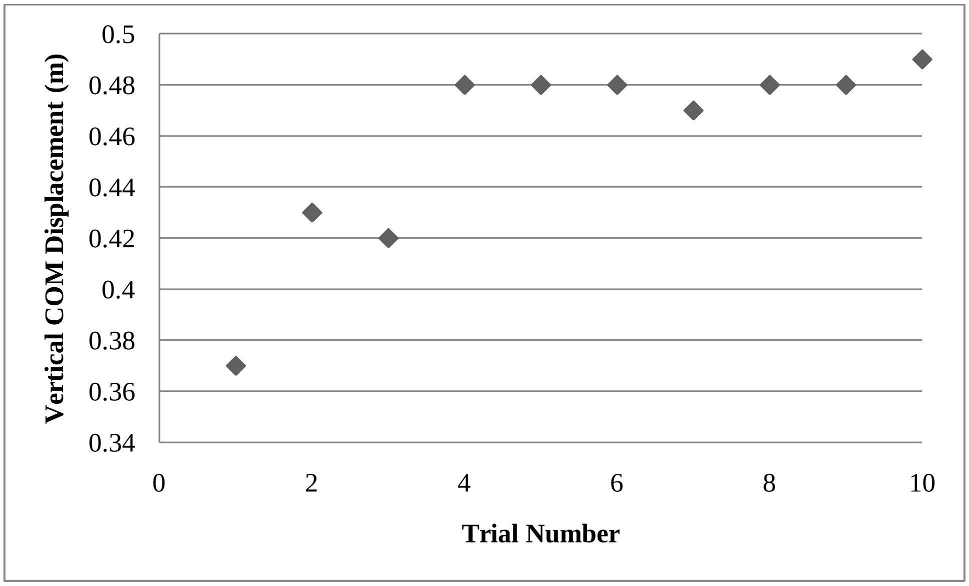

Fig. 7 Relationship between the vertical COM displacement and the trial number for subject ten. The plot documents a large change in the jump heights in the first few trials, this is followed by more stable jump heights.

5.1. Vertical Jump Height and Joint Work Done Summary

From the 20 participants (Table 3), only three had jump heights over 0.50 m, four participants were within the 0.30-0.39 m range, and the remaining eleven participants were between 0.40 and 0.49 m. Subjects 8 and 20 did perform the 10 preferred jump strategy repetitions, but left the force plate during their countermovement in all their trials. These errors were not obvious during the data collection but were recognized during the data analysis. The remaining 18 participants all had 5 jump trials included within their mean vertical jump height score.

Table 3: Individual vertical jump heights and the group mean and standard deviation from three tasks: preferred, hip-dominant and knee-dominant

Subject	Preferred (m)	Hip (m)	Knee (m)
1	0.47	0.41	0.41
2	0.45	0.40	0.39
3	0.40	0.40	0.39
4	0.43	0.38	0.41
5	0.51	0.49	0.46
6	0.42	0.40	0.41
7	0.46	0.42	0.43
8	n/a	0.45	0.45
9	0.42	0.38	0.39
10	0.48	0.39	0.44
11	0.39	0.37	0.34
12	0.43	0.37	0.39
13	0.41	0.37	0.39
14	0.43	0.39	0.39
15	0.59	0.47	0.56
16	0.35	0.33	0.35
17	0.34	0.30	0.33
18	0.51	0.45	0.46
19	0.39	0.34	0.35
20	n/a	0.30	0.32
Mean	0.49	0.39	0.40
St Dev (±)	0.06	0.05	0.05

There were five participants that demonstrated a greater hip than knee contribution with a hip/knee work ratio greater than 1. Four participants had hip/knee work ratios between 0.90-0.99, five were within 0.70-0.89, three within 0.50-0.69 and one that had a hip/knee ratio less than 0.40.

Table 4: The total work done (WD), hip WD, knee WD, ankle WD and hip/knee WD ratio of the preferred jumping task for individual subjects.

Subject	Total WD (J/kg)	Hip WD (J/kg)	Knee WD (J/kg)	Ankle WD (J/kg)	Hip/Knee
1	7.76	3.00	2.64	2.12	1.14
2	6.73	2.95	1.89	1.89	1.58
3	6.37	2.30	2.12	1.95	1.09
4	5.49	1.52	1.82	2.15	0.85
5	8.14	2.94	3.04	2.15	0.97
6	7.64	2.18	3.43	2.03	0.64
7	6.82	1.94	2.75	2.12	0.71
8	n/a	n/a	n/a	n/a	n/a
9	4.87	1.26	2.13	1.48	0.59
10	7.19	2.63	2.18	2.38	1.12
11	6.08	1.63	2.71	1.75	0.61
12	6.77	2.09	2.70	1.98	0.77
13	5.70	1.54	2.07	2.10	0.75
14	7.28	2.67	2.76	1.86	0.97
15	9.17	3.37	3.54	2.26	0.96
16	5.75	1.93	1.93	1.88	1.01
17	4.83	0.67	1.78	2.37	0.38
18	8.29	3.00	3.16	2.13	0.96
19	5.79	1.42	1.92	2.45	0.76
20	n/a	n/a	n/a	n/a	n/a
Mean	6.70	2.17	2.48	2.06	0.88
St Dev (±)	1.18	0.72	0.55	0.23	0.26

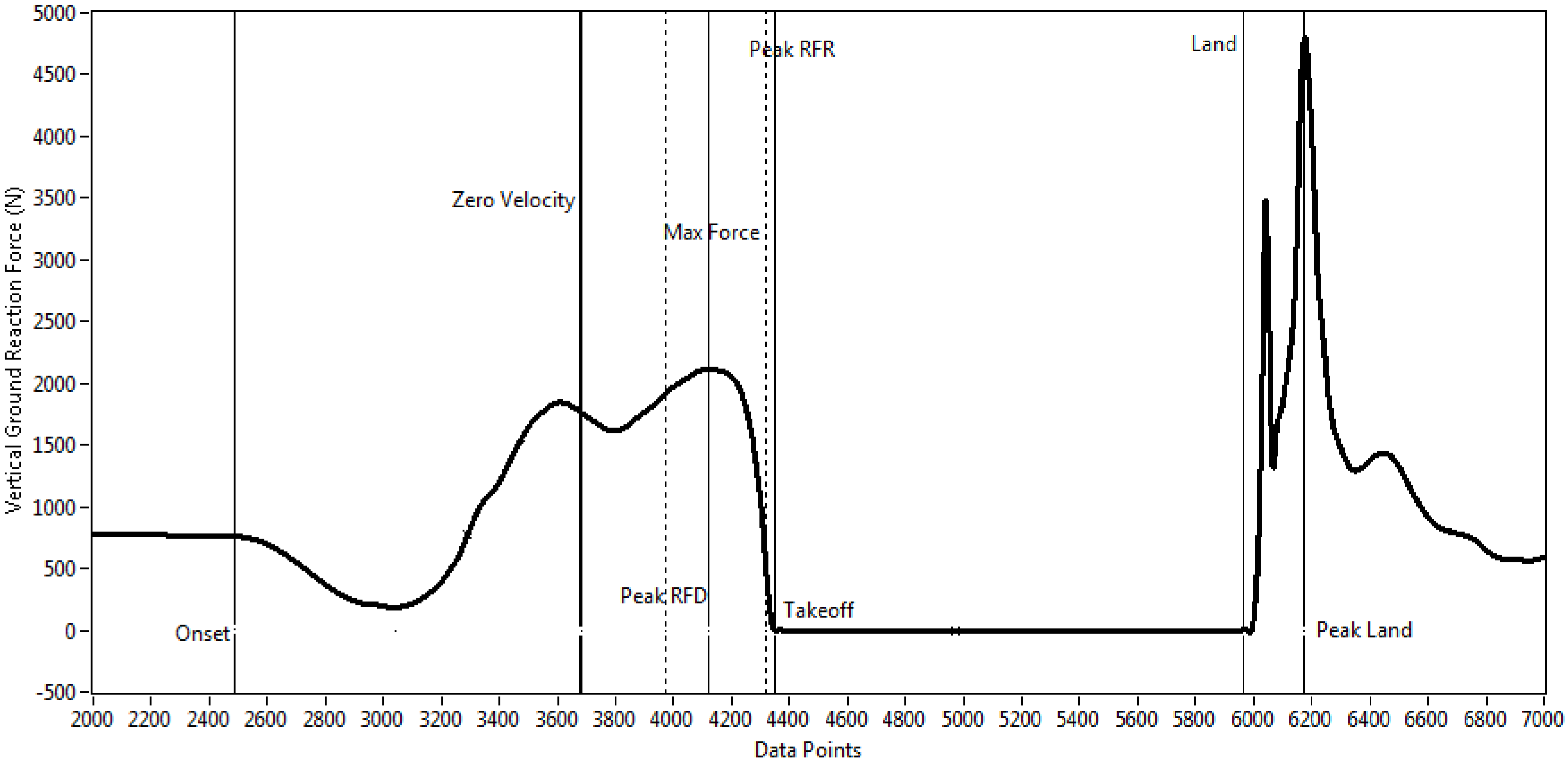

Fig. 8 Time varying vertical ground reaction force signal measured during a single jump from subject #15 (top jumper). Sampling rate was 2400 Hz.

5.2. *Strategy and Vertical Jump Height*

From the preferred jumping task, the total work done by the hip, knee and ankle had a positive and significant relationship with the vertical COM displacement (r(17) = 0.799, p<0.0001). Only the hip (r(17) = 0.786, p<0.0001) and knee (r(17) = 0.593, p=0.0094) had associations with the vertical COM displacement. The ratio of the hip and knee work was positively related to the vertical COM displacement (r(17) = 0.452, p=0.0298) (see Figure 9). A ratio of the hip and knee peak power did not show a significant relationship with the vertical COM displacement.

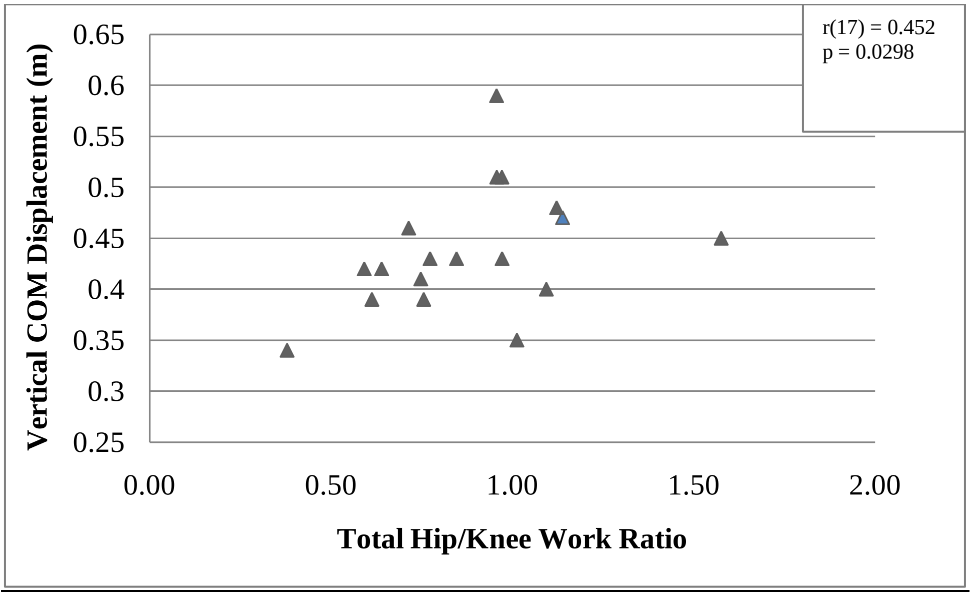

Fig. 9 Relationship between the vertical COM displacement and total hip/knee work ratio of the preferred jumping task. Each data point reflects the participant's vertical jump height (vertical COM displacement) and corresponding hip/knee work ratio.

The hip work done of the preferred task was significantly lower than the hip work done of the hip dominant (t(16) = -1.48, p=0.0793) (see Figure 10). Similarly, the knee work done of the preferred task was significantly lower than the knee work done of the knee dominant jumping task (S(16) = -75.5, p<0.0001). These results demonstrate that the jump task training was effective in changing the mechanics in order to facilitate hip or knee dominance. The change in the hip/knee work ratio after training was not statistically different between the hip and knee dominant tasks (t(16) = 1.20, p=0.2477).

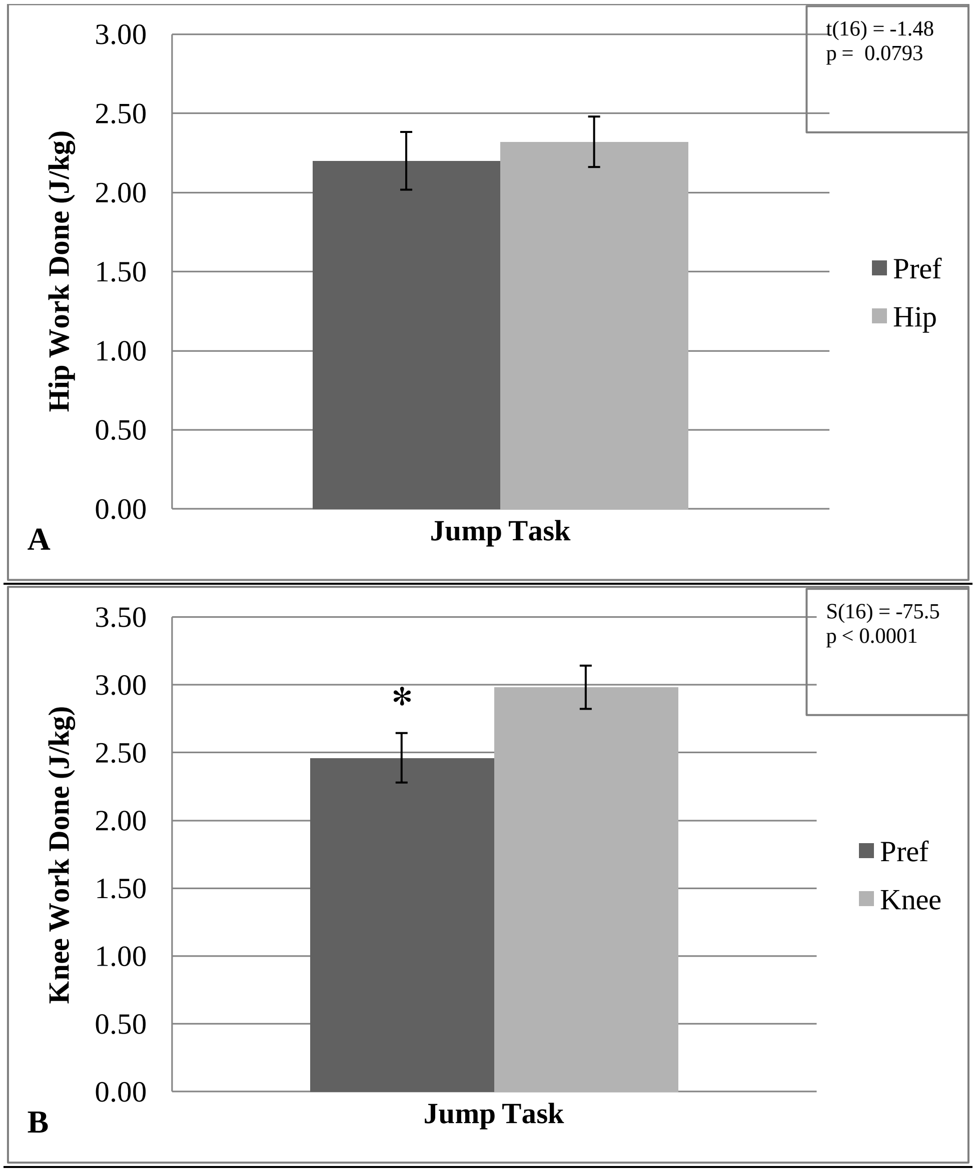

Fig. 10 (A) Comparison of the hip work done of the preferred and hip-dominant tasks, and (B) compares the knee work done of the preferred and knee-dominant tasks. Each bar in figure 10 represents the group mean and has an attached standard error bar.

The vertical COM displacement was significantly lower in the hip dominant jumping task than the knee dominant task (S(19) = -45.5, p=0.0287) (see Figure 11).

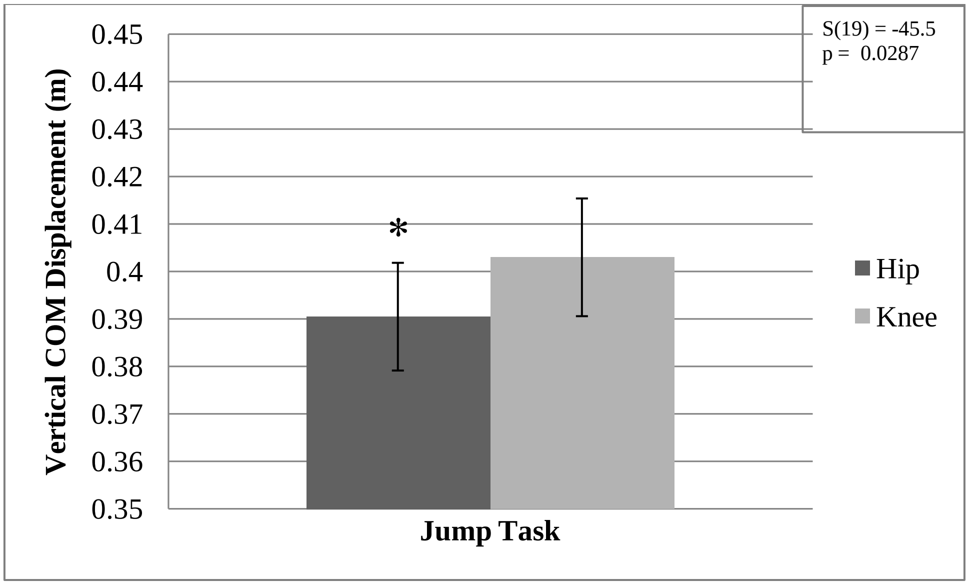

Fig. 11 A comparison of the vertical COM displacement of the hip dominant task to the knee dominant task. Each bar represents the group mean and has an attached standard error bar.

From the three jumping tasks the preferred task yielded the highest vertical COM displacement (as seen in Figure 12).

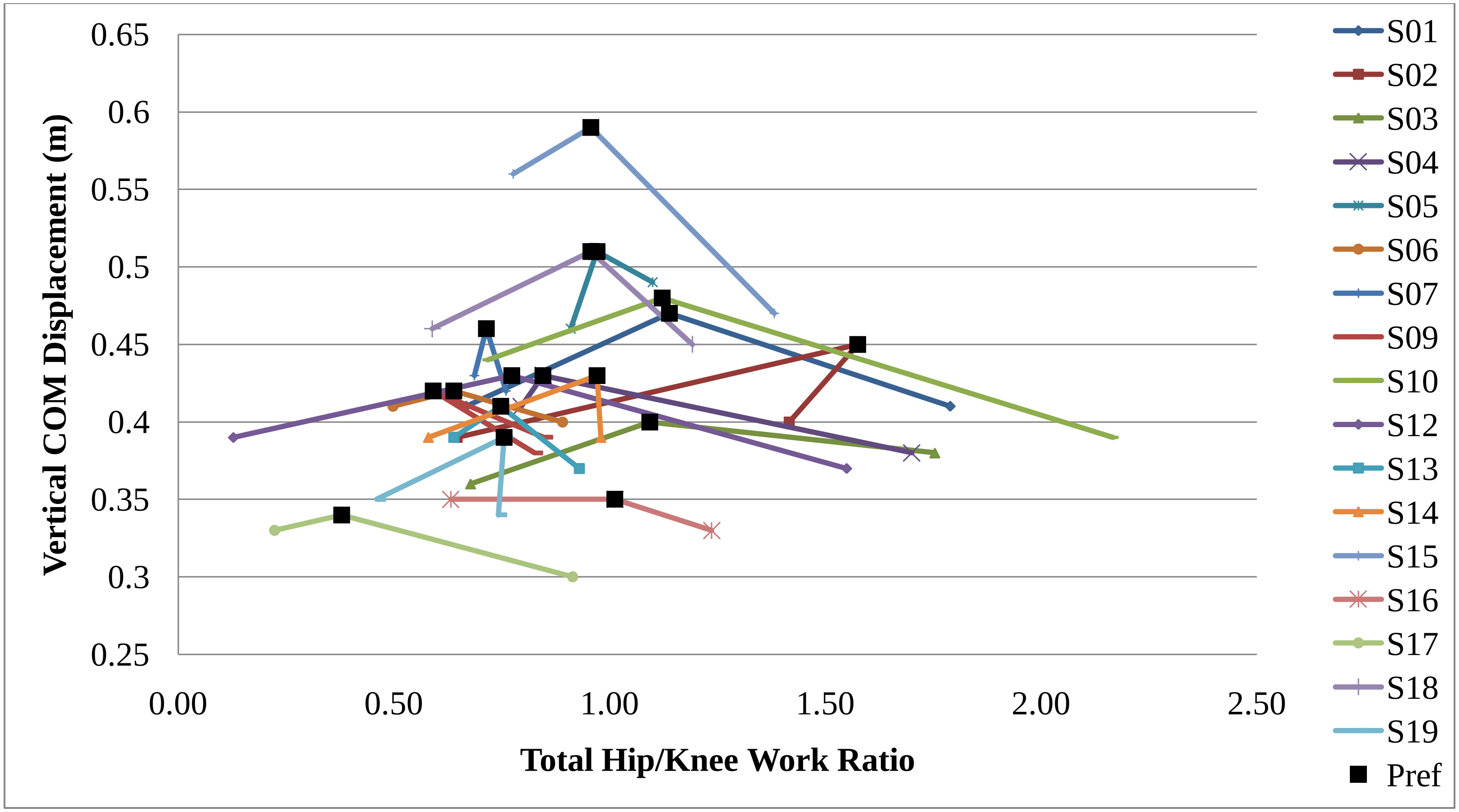

Fig. 12 Relationship between jump performance (vertical COM displacement) and hip/knee work ratio. Lines represent data from each individual subject. The three data points reflect the three task conditions (knee-dominant, preferred and hip-dominant) with the preferred task highlighted with a black marker. Each participant's data series is presented in specific order (starting from the left) knee-dominant, preferred and hip-dominant jumping tasks.

There was a positive trend between the hip/knee work ratio and the peak RFR, but statistical significance was not attained (r(17) = 0.420, p=0.0823) A positive association existed between the hip/knee work ratio and peak RFD (r(17) = 0.476, p=0.0457) (as seen in Figure 13). .   In addition, the peak hip power appeared to have a positive relationship with the peak RFR, but this was not statistically significant (r(17) = 0.457, p=0.0565).

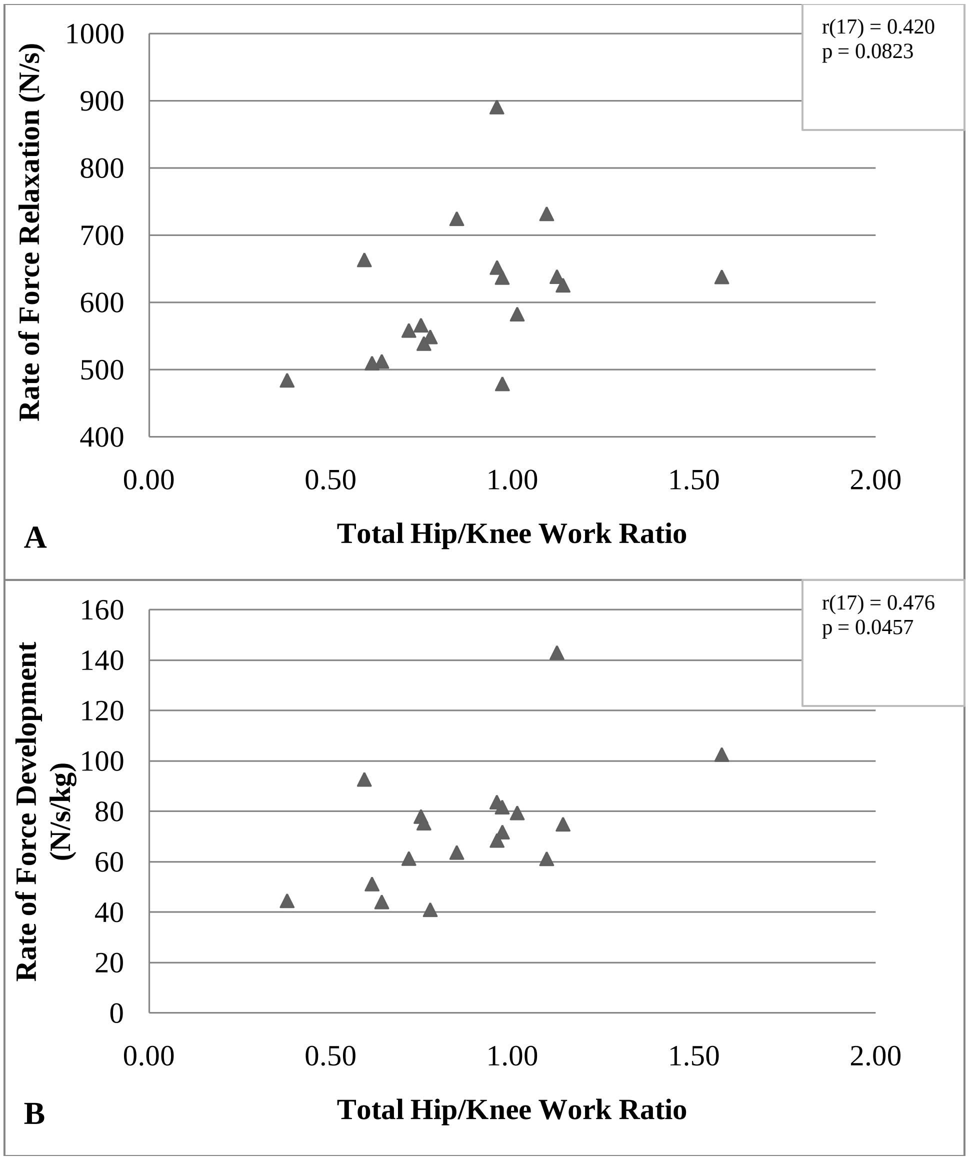

Fig. 13 (A) Relationship between the peak RFR and the hip/knee work ratio. Each data point reflects the participant's peak RFR and corresponding hip/knee work ratio. (B) Relationship between the peak RFD and hip/knee work ratio. Each data point represents the participant's peak RFR and corresponding hip/knee work ratio.

There was a positive association between the vertical COM displacement and Peak RFR (r(17) = 0.488, p=0.040). There were positive trends between the vertical COM displacement and peak RFD (r(17) = 0.381, p=0.1186), and vertical COM displacement and max force (r(17) = 0.356, p=0.1467), but neither were statistically significant. The max force had a positive relationship with the peak RFR (r(17) = 0.608, p=0.0075), additionally the peak RFD had a positive association with the peak RFR (r(17) = 0.490, p=0.0389). The peak RFD positively associates with the max force (r(17) = 0.713, p=0.0009). These results demonstrate possible linkages between the force plate variables (RFD, max force and RFR), and these variables additionally appear to positively link to jump height.

Trunk and leg length were evaluated and no association was present between the ratio of trunk/leg length and the hip/knee work ratio. Individually, leg length tended to increase with a rise in the hip/knee work ratio (r(17) = 0.363, p=0.0695) and had positive relationship with the total hip work done (r(17) = 0.407, p=0.0467) (see Figure 14). Trunk length only had a relationship with the total ankle work done (r(17) = -0.548, p=0.0186).

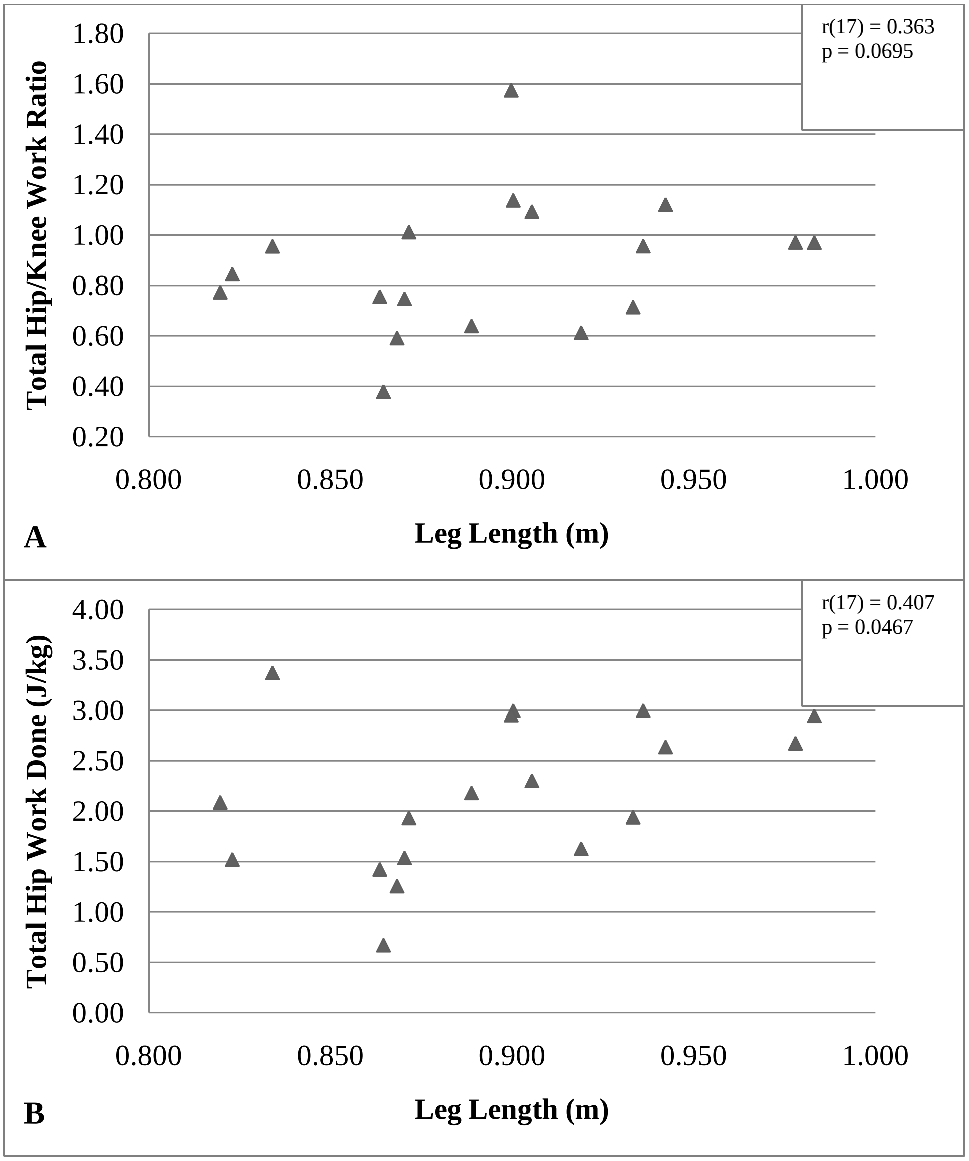

Fig. 14 (A) Relationship between the hip/knee work ratio and leg length. Each data point reflects the individual's hip/knee work ratio and corresponding leg length. (B) Relationship between the hip work done and leg length. Each data point reflects the participant's hip work done and corresponding leg length.

5.3. Mechanics and Muscle Activation

For the preferred jumping task, there were no significant relationships between the GMax/BFem peak activation ratio and hip work done for both the right (r(17) = -0.399, p=0.1066) and left (r(17) = -0.207, p=0.4089) sides. Similarly, no significant relationships existed between the GMax/BFem max rate of activation ratio and peak hip power for both the right (r(17) = -0.315, p=0.2033) and left (r(17) = -0.346, p=0.16) sides. Possible relationships between the individual muscles (GMax and BFem) and the hip mechanics were explored and revealed no significant or apparent relationships. Analysis of the knee extensors revealed a significant positive association (Figure 15) existed between the VLat/RFem peak activation ratio and knee work done for only the right side (r(15) = 0.644, p = 0.0071). There were no significant relationships found between the VLat/RFem max rate of activation ratio and peak knee power in either the right (r(15) = -0.038, p=0.8882) or left (r(15) = 0.165, p=0.5421).

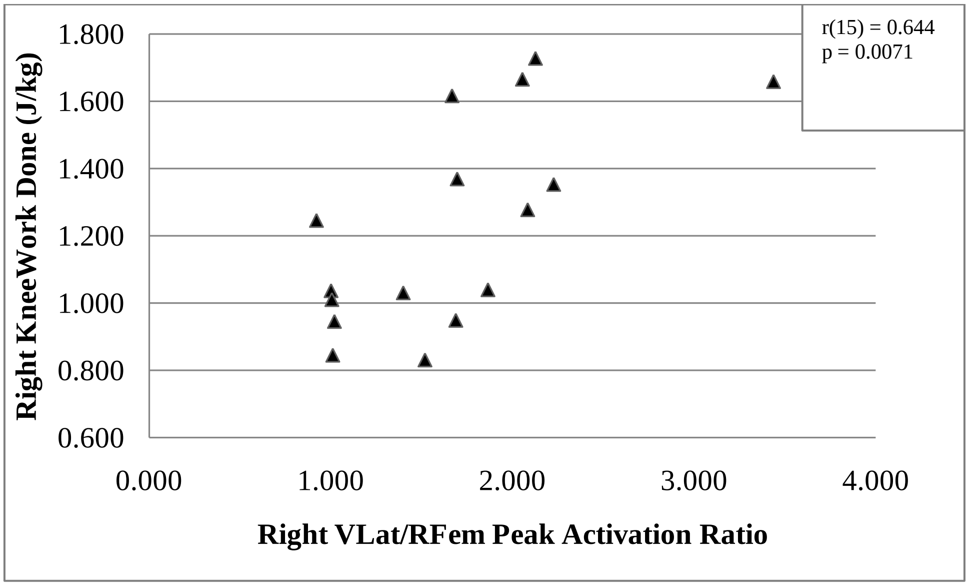

Fig. 15 Relationship between the right knee work done and VLat/RFem peak activation ratio. Each data point reflects the participant's right knee work done and corresponding right VLat/RFem peak activation ratio.

When comparing the hip and knee-dominant tasks (as shown in Figure 16), it was found that the ratio of GMax/BFem total muscle activity was lower in the hip task than the knee for both the right (S(17) = -62.5, p=0.0047) and left (S(17) = -80.5, p<0.0001) sides. The right and left GMax activity was lower in the hip dominant task than the knee, but only significant for the right side (S(18) = -56, p=0.0223). The BFem activity was higher in the hip-dominant task compared to the knee dominant task, but this difference was not significant for either the left or right side.

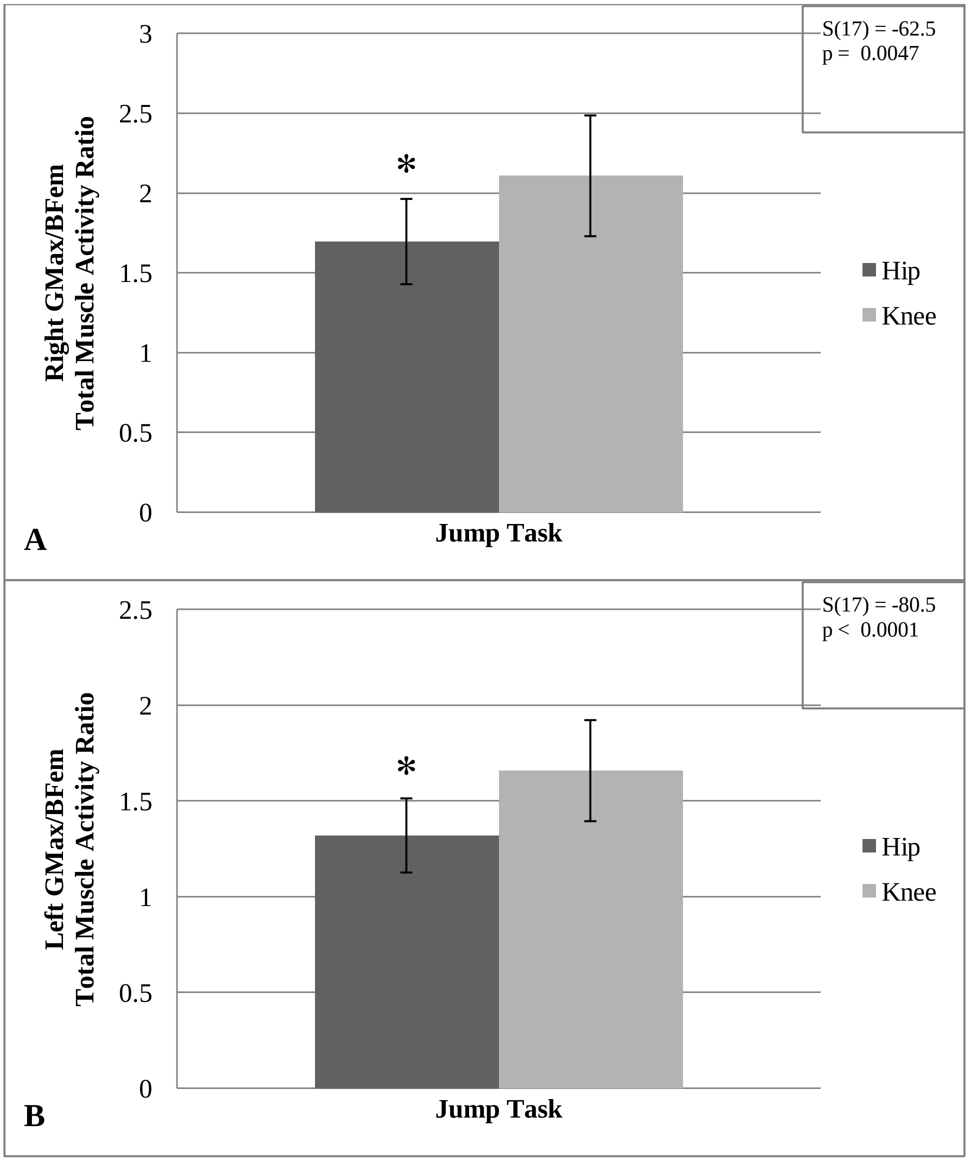

Fig. 16 (A) Comparison between the right GMax/BFem total muscle activity ratio of the hip dominant and knee dominant tasks. (B) Comparison between the left GMax/BFem total muscle activity ratio of the hip and knee dominant tasks. Each bar in figure 16 reflects the group mean and has an attached standard error bar.

The ratio of VLat/RFem total muscle activity was higher (see Figure 17) in the hip dominant task than the knee dominant task for both the right (S(17) = 43.5, p=0.0599) and left (S(18) = 84, p=0.0002) sides, but was only statistically significant for the left side. Individually, the VLat and RFem had significantly lower activity in the hip task than the knee dominant task for both right and left sides: RVLat (S(17) = -60.5, p=0.0065), LVLat (S(18) = -64, p=0.008), RRFem (S(18) = -90, p<0.0001), LRFem (S(18) = -83, p=0.0003).

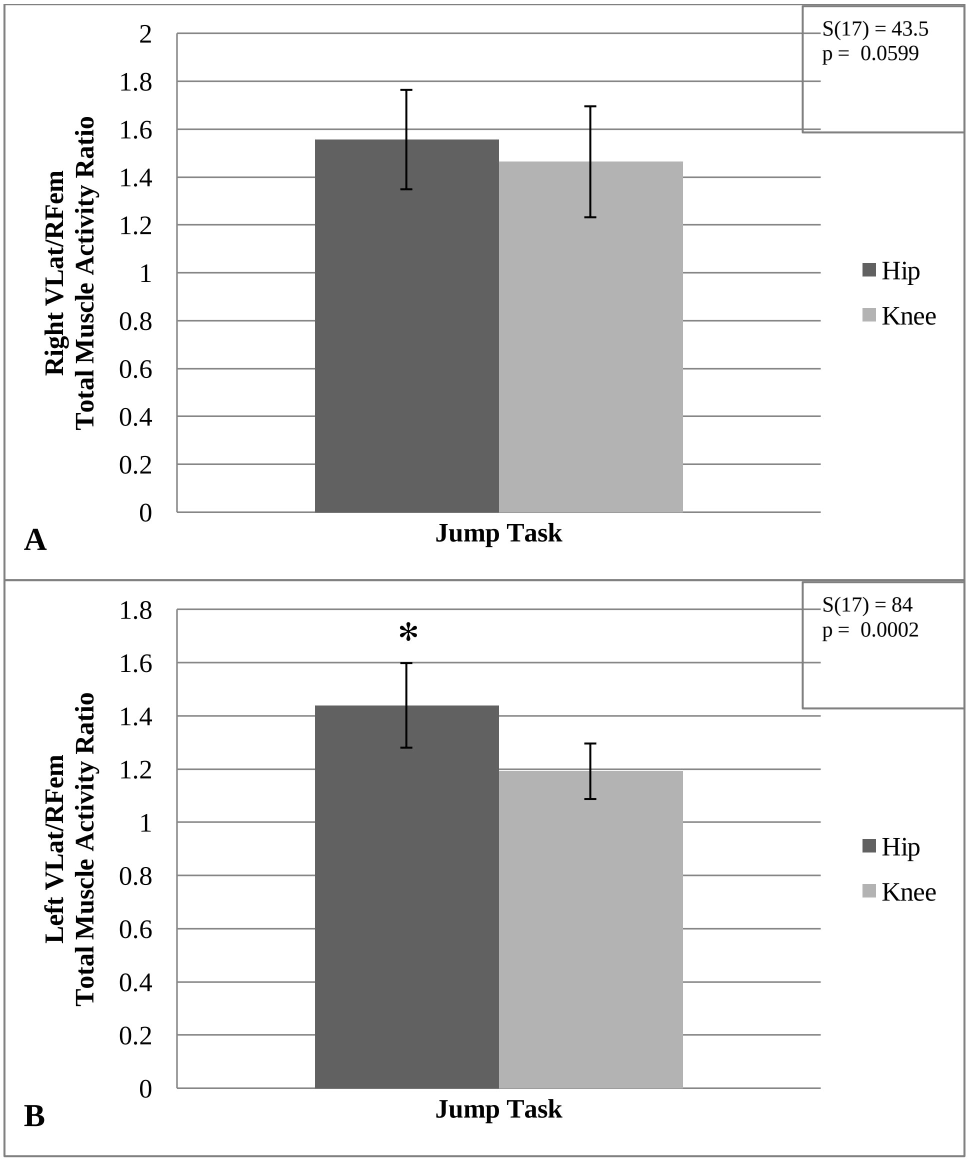

Fig. 17 (A) Comparison between the right VLat/RFem total muscle activity ratio of the hip dominant and knee dominant tasks. (B) Comparison between the left VLat/RFem total muscle activity ratio of the hip and knee dominant tasks. Each bar in figure 17 reflects the group mean and has an attached standard error bar.

Post-hoc analyses were completed with individual muscle activity amplitudes, muscle activity range and performance variables such as RFR, RFD and max force. The peak RFD had a negative significant association with the peak LGMax activity (r(17) = -0.505, p=0.0327). The RGMax appeared to negative association (Figure 18) with the max force for both the right (r(17) = -0.525, p=0.0252) and left (r(17) = -0.449, p=0.0617) sides, but the left side was marginally not significant.

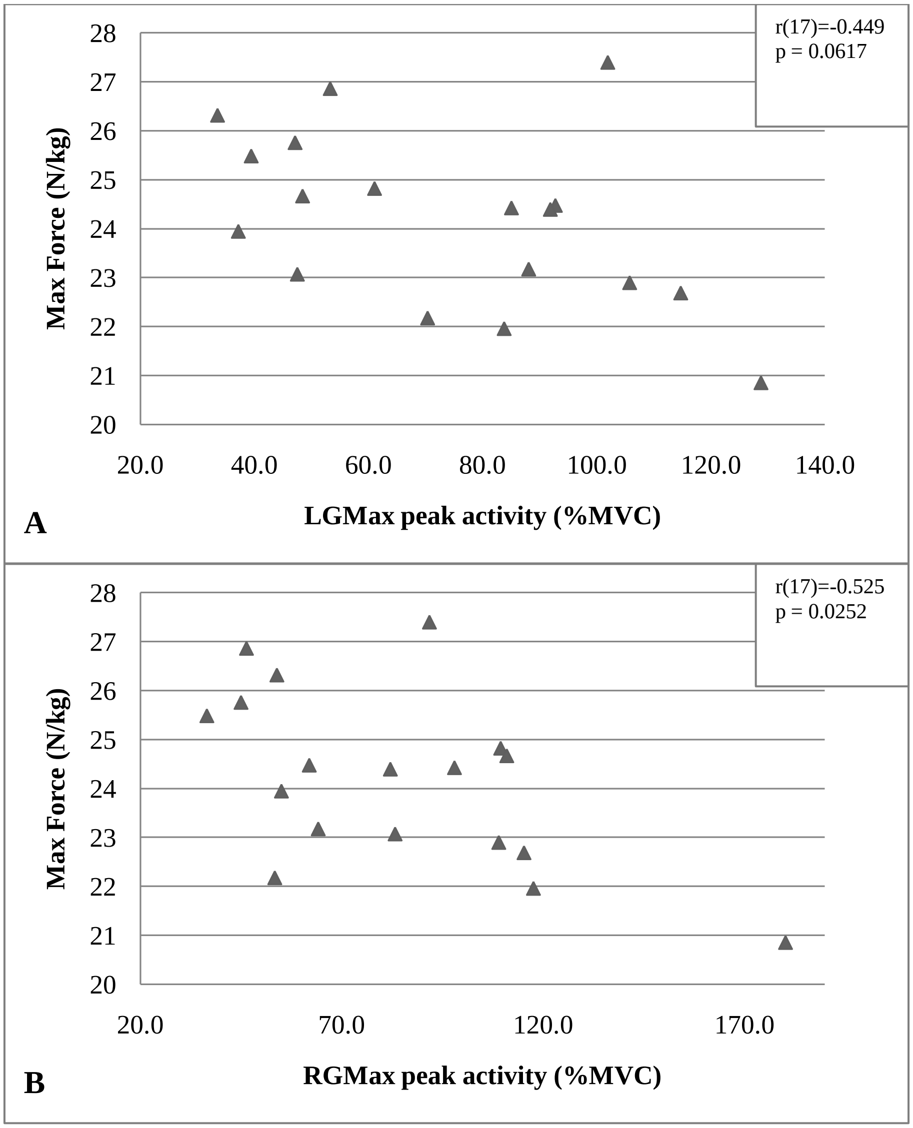

Fig. 18 Relationship between the max force and LGMax (A) and RGMax (B) peak activity. Each data point reflects each participant's max force and corresponding right or left GMax peak activity. Both A and B illustrate higher peak GMax activity may negatively influence the max force.

The range of the timing of muscle activity peaks for the lower limb muscles (Figure 19) displayed a negative trend with the peak RFR (r(15) = -0.491, p=0.0534) and negative relationship with the max force (r(15) = -0.559, p=0.0244).

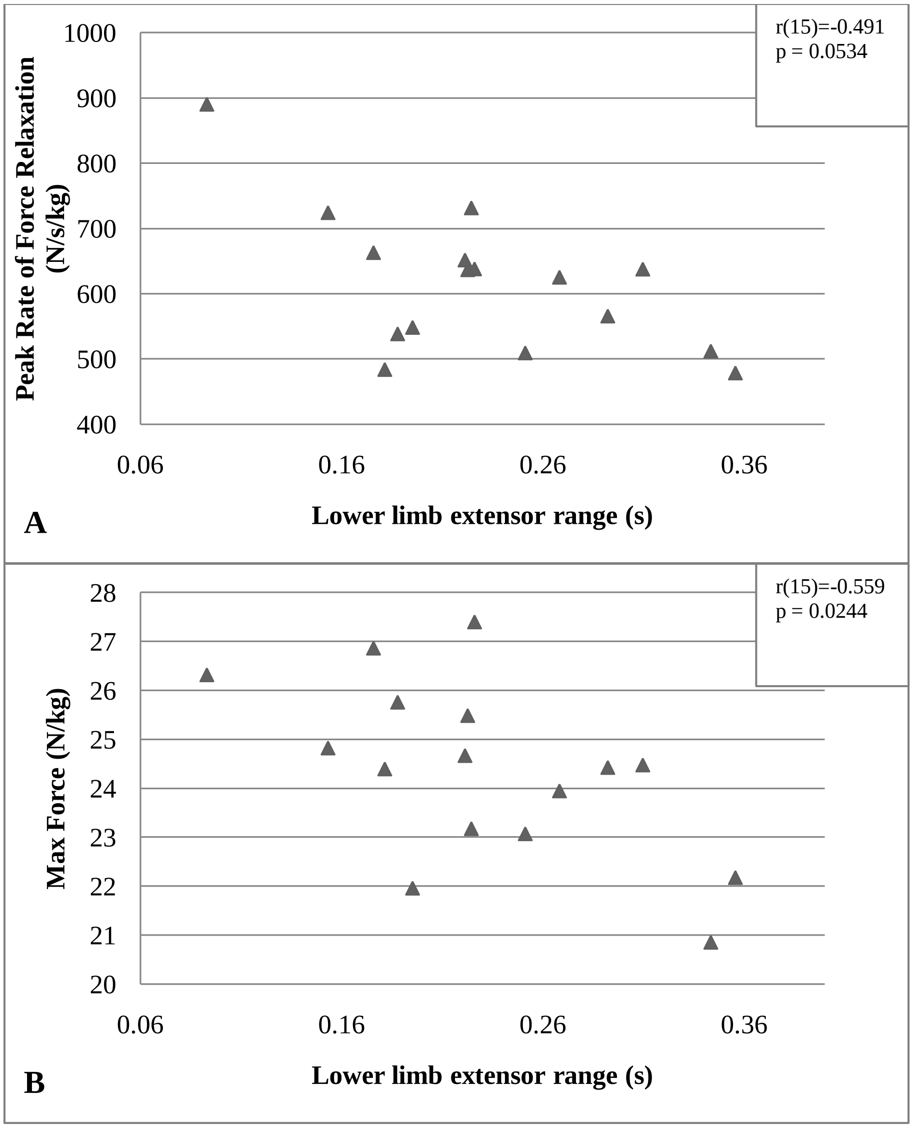

Fig. 19 (A) Relationship between the peak RFR and lower limb extensor range. Each data point represents the individual's peak RFR and corresponding lower limb extensor range. (B) Relationship between the max force and lower limb extensor range. Each data point reflects the participant's max force and corresponding lower limb extensor range. The decreased duration between the first peak and last peak of the lower limb muscles could benefit the peak RFR (A) and max force (B).

5.4. Lumbar spine and hip mechanics

Lumbar spine velocity had a negative significant association (Figure 20) with hip velocity of both the right (r(15) = -0.468, p=0.0339) and left (r(15) = -0.529, p=0.0175) sides. There was no relationship between the hip velocity and the vertical COM displacement.

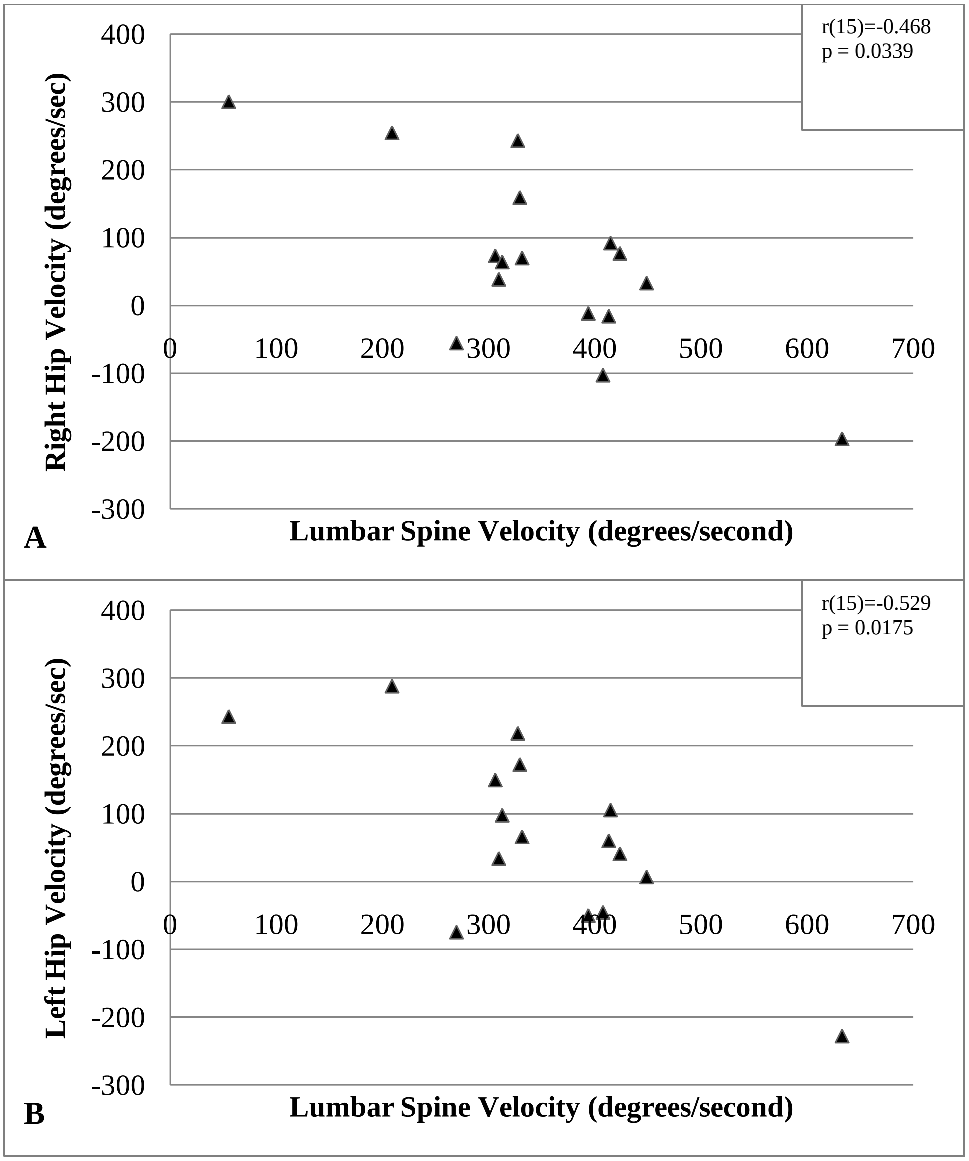

Fig. 20 Relationships between the lumbar spine velocity and right (A) and left (B) peak hip velocity.

Analysis of the trunk muscle activation peak amplitude showed that there was a positive relationship between the REO and vertical COM displacement (r(15) = 0.591, p=0.0159). A positive trend existed between the vertical COM displacement and LEO peak activity but the result was not statistically significant (r(15) = 0.405, p=0.1199). In addition the LIO showed a positive association with the vertical COM displacement(r(16) = 0.508, p=0.0372) (as seen in Figure 21).

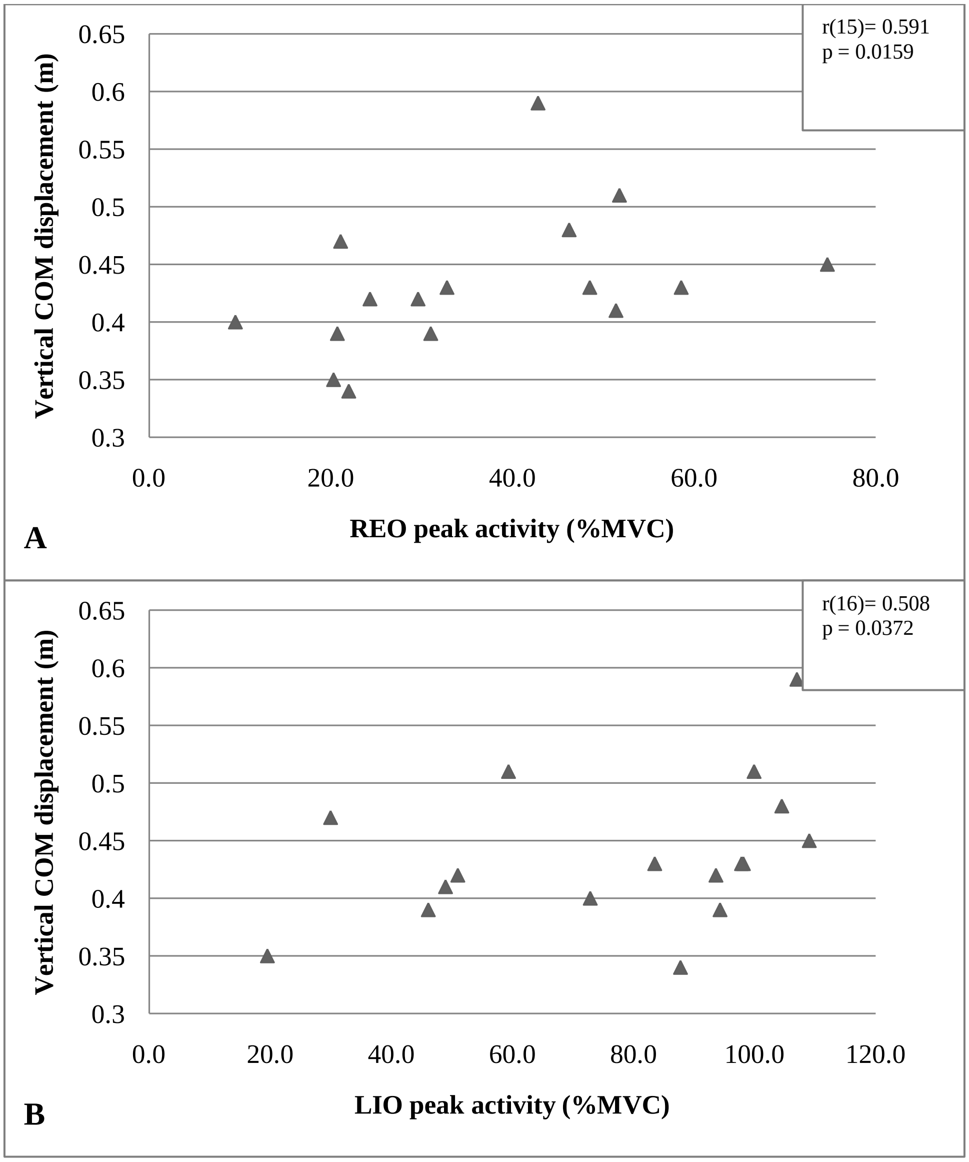

Fig. 21 (A) Relationship between the vertical jump height (vertical COM displacement) and REO peak activity. Each data point reflects each participant's vertical jump height and corresponding REO peak activity.

(B) Relationship between the vertical jump height and LIO peak activity. Each data point reflects the individual's vertical jump height and corresponding LIO peak activity.

Observation of the EMG signals for the trunk muscles revealed that after the start of propulsion, peak activation was closer to the end of the propulsion phase than the onset. Each participant appeared to have the peaks of their trunk muscles align differently from one another, some closer and other further apart. For instance in figure 22(A) shows the peaks within a range of 32ms, while figure 22(B) shows the peaks further apart and within a range of 204ms. By quantifying the range between the first peak after the start of propulsion and last occurring peak, it was determined that the max force tended to increase with a decrease in the trunk muscle range and max force (r(17) = -0.461, p=0.0623) but was not significant. The LIO peak activity had a positive association with the max force (r(16) = 0.553, p=0.0210).

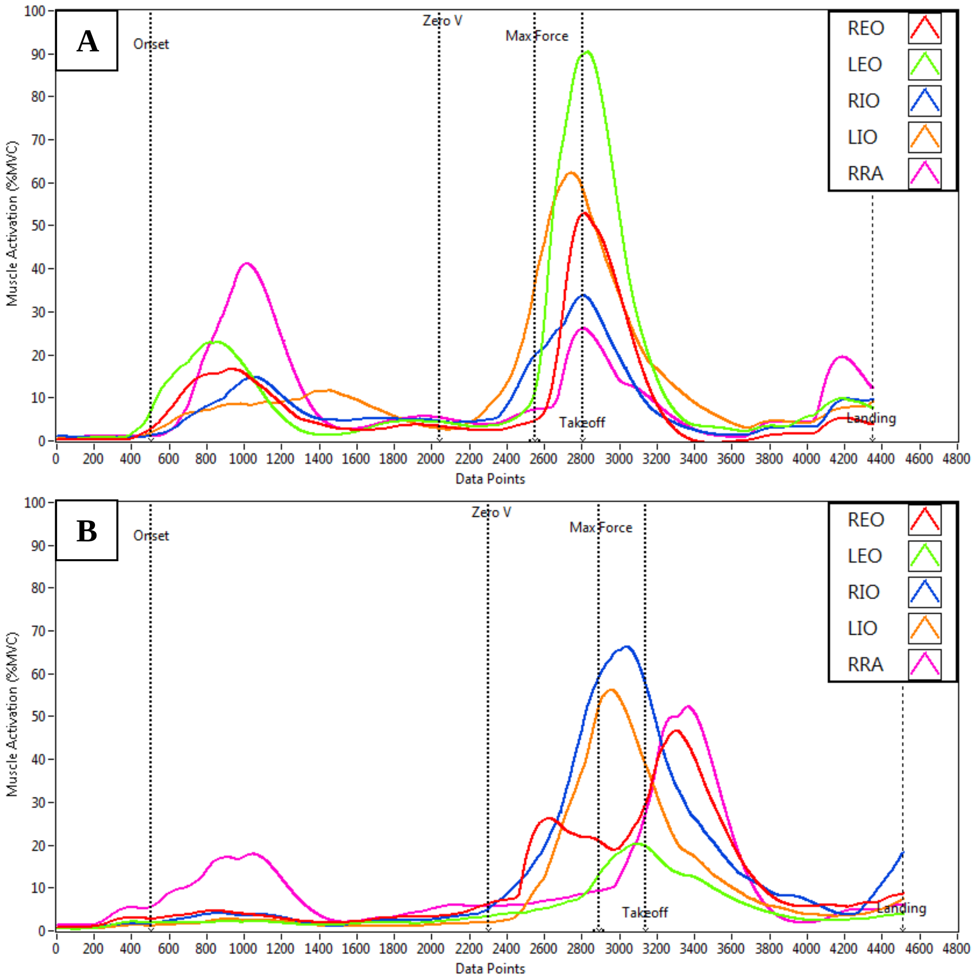

Fig. 22 Linear envelope EMG of two participants 5 (A) and 6 (B). Participant 5 skilfully activated the trunk muscles aligning the peaks within a range of 32ms, while participant 6 activated the trunk muscles near takeoff but aligns the peaks within a larger range of 204ms. Sampling rate was 2400 Hz. The time of peak activation was relative to the "ZeroV" or the start of propulsion.

6. Discussion

The overall objective of this study was to determine if greater hip than knee contribution was more effective in enhancing standing two-foot vertical jump height. Hip dominance appears to be more effective than knee dominance in enhancing jumping performance as indicated by the results from the preferred jumping task. However, the within-subject comparisons between the trained hip and knee dominant tasks did not support the results of the preferred jumping task. The disagreement with the results from the preferred task may be due to limited training time and its inability to optimize the jumping strategy in each task.

The second objective was to understand links between the muscle activation and the resultant mechanical outputs. It was revealed that greater biceps femoris than gluteus maximus activity enhances the hip work done, while both the vastus lateralis and rectus femoris activity increases with rising knee work. The findings suggest that the role of the bi-articular muscles may be dependent on the jumping strategy and functions to both transfer and generate mechanical work and power.

The third objective was to examine the coupling between the lumbar spine and hip. It appears that lower lumbar spine velocities influence higher hip velocities at takeoff in the jumping movement. The more important finding resulted from the indirect examination of spine stiffness through the analysis of the trunk musculature. Higher trunk muscle activity and tighter coupling may have augmented spine stiffness, which positively influenced the vertical jump height and the max force.

The following sub-sections will discuss each of the objectives and results mentioned above and further highlight study limitations, literature comparisons, additional findings and possible avenues for future investigation. The discussion will conclude with a section that discuss the implications the findings have for training two-foot vertical jump performance.

6.1. Strategy and Vertical Jump Height

The initial hypothesis was that greater hip than knee contribution would positively influence jumping performance and the current results partially supported this prediction. The examination of the individual joint mechanics in the preferred jumping task documented that both the hip and knee work done were strongly related to jump height, possibly suggesting that a coupling of the two joints would be most effective. However, after comparing a ratio of the two variables (hip/knee) to jump height it appears that greater hip than knee contribution benefits two-foot vertical jump performance. Since the investigation of the preferred task was a comparison between subjects, it was not possible to control for factors such as anthropometry and muscle physiology (e.g. muscle morphology). This was the rationale for conducting the related within-subject comparisons. We did attempt to limit some of the between subject variability by selectively recruiting high-level athletes (competitive varsity) from specific sports were dependent on jumping (e.g. basketball, volleyball and long-jump).

The aim of the within subject comparisons was to explore influences of jump strategy on jump performance without the confound of between subject variability. Important to our findings were that the methods used to encourage hip and knee dominance were successful (Figure 10). However, while it was possible to train and increase hip or knee work within subjects, the study did not reveal a benefit to jump height based on an increase in the hip work within individuals. In fact, the knee dominant task performance was just over 1 cm greater than the hip dominant task. The absence of performance effects in this part of the study may have been due to the relative novelty of the learned tasks (learn the new movement within ten minutes) limiting the participant's maximum jumping ability. In support of this idea, several participants disclosed at the end of the study that either one or both trained tasks were challenging to learn within the training time period. A consistent observation was that the preferred jumping task had the highest jump heights. The preferred jumping task had been practiced by the participants many times in their respective sports and this over learning may have led to optimization of the movement strategy that was not achievable in a 10 minute training period. Optimization of a movement strategy would effectively minimize any control challenges to the central nervous system that include but are not limited to: (1) maximizing linear impulse through the coordination of multiple muscles, joints and segments, (2) minimizing angular rotation of the centre of mass (COM) by optimally directing the line of force application at the ground, and (3) allowing for muscular co-contraction to occur to reduce joint compliance but still allow for necessary joint moment development. In this study, training time for the hip and knee dominant tasks would have been extended but the collection period itself was approximately 4 hours and the risk of losing motivation and mental fatigue may have increased.

Alternatively, the optimal motor strategy and resultant mechanical outputs may be set, regardless of whether they can be manipulated, and therefore any change would result in lower jumping performance. An optimal strategy (preferred hip/knee work ratio), unique to an individual may be linked to their anthropometry. There was some indirect support for this idea. For example, leg length had a positive association (Figure 13) with the hip/knee work ratio and total hip work done, possibly suggesting that those with longer legs are better suited for developing more work at the hip than the knee. Further exploration into the links between the anthropometry and the optimal strategy is required. However, if definite links exist then improving jumping performance may not be achieved by enhancing hip mechanics, but rather through continuous practice of the strategy to optimize control.

Another variable that could influence the hip and knee contribution to the total work done on the COM is the use of arm swing. The work done by the upper extremities has been shown to contribute less than 1% to the total work done (Hara et al., 2008), thus its direct effect to jump height is likely minimal. However, the inclusion of arm swing increases the amount of work done at each joint by applying an additional load to the lower body through the additional forward tilting of the trunk. For example, Hara et al. 2008, documented that work done by the hip, knee and ankle increased approximately 8%, 28% and 17% respectively with arm swing, with the hip exhibiting the highest magnitude of work done. In this study, all the participants were instructed to use arm swing while jumping. The objective was to explore how the hip and knee contributions influenced jumping performance, and thus we were not initially concerned with how different arm swing strategies would influence the lower limb joint mechanical outputs.

The literature has suggested only a hip dominant or knee dominant strategy is used when performing jumping movement, but the present study indicated that varying contributions of the hip and knee can be used to perform a two-foot standing vertical jump. Two examples of exclusive hip or knee dominant control are the findings of Hubley and Wells (1983) that suggest higher knee than hip and ankle is exhibited, and Fukashiro and Komi (1987) that suggest higher hip than knee and ankle is exhibited. The former study averaged their data across subjects, but examination of the individual strategies reveal strategies that differ in the hip and knee contributions. The latter study was limited to only one participant and thus its findings are difficult to generalize to larger populations. In terms of performance, the results from the preferred task suggesting that enhancement in the hip mechanics may be beneficial to vertical jump height is in partial agreement with Aragon-Vargas and Gross (1997). Their study concluded that the peak hip power was a predictor of better jumping performance, whereas this study provides some evidence for the importance of hip work.

Although, the notion of greater hip than knee contribution benefits vertical jump height was not entirely supported there appear to be other benefits of enhanced hip mechanics such as higher peak RFR and RFD. The peak RFR, RFD and max force were positively linked to the vertical jump height. Therefore, this provides indirect support for enhancing the hip mechanics to benefit vertical jump performance. Improving the hip mechanics would enhance these performance variables because of its link to the trunk through the articulation of the pelvis. It has been documented that the order of lower limb joint reversal from flexion to extension is proximal to distal (Bobbert et al., 1988). Therefore, the knees and ankles do not extend until the hips have started extending and the trunk is in a more upright position. Delays in extending the trunk would delay the onset of extension at the more distal joints. The time to move the trunk is likely reduced by enhancing the hip work, but failure to generate the necessary hip work would increase the time to bring the trunk upright; this would consequently reduce the vertical acceleration of the trunk. Therefore, the potential for a higher acceleration and TOV of the COM are limited, since only the knees and ankles remain in maximizing these variables.

It should be noted that there was considerable between-subject variation in the hip and knee contributions during the preferred jump. The potential source for this variability is likely partially explained by biological differences (anthropometry and physiology). In addition, the differences may have arisen from different training and jump movement experiences. The variation in vertical jump height that was also noteworthy comparing across individuals could have been importantly linked to the specific strategies used by individuals. However, there is the possibility that motivation, effort and state of arousal to perform the jumping tasks may have influenced performance on the day of lab testing. Possible ways to limit their influence include but are not limited to: (1) providing trial to trial feedback to each participant regarding their jump height, (2) playing music to influence arousal levels, and (3) providing vocal encouragement.

To conclude, higher hip than knee contributions appears to benefit jumping performance as supported by the results from the preferred jumping task and is indirectly supported by the positive influence the hip mechanics have on the peak RFR and RFD. The within-subject comparisons of the hip and knee dominant jumping tasks failed to provide additional support, which was likely due to the novelty of the task and limited training time to optimize the movement strategy. Therefore, future research into longer term training (e.g. days, weeks and months) of the movement strategy is required to provide definitive support for higher hip than knee contribution benefiting vertical jump performance. Lastly, the consistent observation of the preferred jumping task resulting in the highest jumping performance (amongst the three tasks) would suggest that the practicing and further optimization of the control is important to improving jump height.

6.2. Relationships between Mechanical Outputs and Motor Strategy

There was an interest in determining whether any links existed between the activation of the hip extensors and mechanical outputs of the hip, and conversely the activation of the knee extensors and the knee mechanics. It was hypothesized that greater gluteus maximus than biceps femoris activity would enhance the hip mechanics. This was not supported by either the results of the preferred jumping task or comparisons between the hip and knee dominant tasks. With the knee extensors there was no hypothesis as it was uncertain how the activation would influence the mechanics. It was revealed from the preferred jumping task that knee work increased with higher peak activation of the vastus lateralis than the rectus femoris. This result was initially contradicted by the findings from the within-subject comparisons of the hip and knee dominant tasks. However, further analysis documented higher activity of both the VLat and RFem in the knee dominant task.

The lack of support for the gluteus maximus being more important for enhancing the hip mechanics was not expected. The actions of the bi-articular BFem are to extend the hip and flex the knee, and thus its ability to have greater influence on enhancing the hip mechanics in comparison to the mono-articular GMax did not seem reasonable. Initially to determine if one muscle had greater influence than the other, a ratio of the activation of both muscles was formed (GMax/BFem). However, when each muscle’s activity was examined, the results revealed that the GMax activity was higher in the knee dominant task, while the BFem activity appeared to be higher in the hip dominant task. One possible explanation could be muscle length differences of the BFem between the hip and knee dominant tasks. The BFem increased in length during the initial countermovement because of the greater hip flexion and limited knee flexion and anterior translation. Lengthening the hamstrings improves its potential to generate mechanical work and power. Therefore it may be probable that the GMax is not solely responsible for enhancing the hip mechanics. In contrast, the BFem may have shortened in length during the countermovement of the knee dominant task, thus limiting its potential to generate mechanical work and power. Here, the GMax must be the main contributor in enhancing the hip mechanics, while the BFem functions more to transfer the work and power.

With the knee extensors, links between their activity and the mechanical outputs were unclear. The result of the preferred task revealed that the mono-articular vastus lateralis appeared to have a greater role in enhancing the knee mechanics than the bi-articular rectus femoris. The within-subject comparisons of the hip and knee dominant tasks initially provided a contradiction to the finding from the preferred task. As was the case with the hip extensors a ratio between the two muscles (VLat/RFem) was used to establish relationships and task differences. For that reason, additional analysis of the individual muscle activity was completed. The activity for both the VLat and RFem were higher in the knee task than the hip dominant task. This would appear to be reasonable based on the training of each joint dominant task. The RFem muscle length shortens or does not change in the hip dominant task during the countermovement and probably functions in transferring work and power. In the knee dominant task the RFem lengthens with limited hip flexion and greater knee flexion, therefore increasing its potential to generate mechanical work and power.

One possible limitation was that the analysis of the EMG between subjects required the signals to be normalized. In this study, the signals were normalized to the subject's maximum voluntary contraction to create a percentage (%MVC). If the voluntary maximum used for normalization was sub-maximal this would inflate the values, and ratios for the across subject analysis would be erroneous. A few steps were taken to combat possible issues: (1) three repetitions of the MVC protocol were performed and the maximum from the 3 was used for normalization, (2) EMG signals were carefully examined after collection, those trials that contained artefacts were removed from the data analysis, and (3) within subject-analysis was conducted using IEMG to provide some comparisons to the normalized data.

The role of the hamstrings documented in this study does not fully agree with previous studies in the literature. The hamstrings primary function has been described as transferring mechanical power and work rather than generating it (Gregoire et al., 1984, Bobbert et al., 1988, Nagano et al., 2005). This study suggests that the role of the bi-articular muscles is strategy dependent, because in certain circumstances there is a greater potential to enhance the joint mechanics via the generation of mechanical work and power. In addition, the specific strategy (hip or knee dominant) that was performed was not fully disclosed in the prior literature. Therefore it is possible that the executed strategy facilitated the bi-articular muscles to function in transferring rather than generating mechanical work and power. The gluteus maximus has been described as being the main generator of hip work and power (Gregoire et al., 1984, Bobbert et al., 1988, Nagano et al., 2005). The results in the present study revealed that this muscle was not highly active as the hip mechanics were enhanced. The shared contribution with the hamstrings may be possible, but the gluteus maximus has additional actions at the knee through fascial connections with other muscles. It has been shown that per unit of force the gluteus maximus has greater potential than the vasti to accelerate the knee toward extension (Arnold et al., 2005). Therefore, these actions at the knee may have further limited its ability to enhance the hip mechanics in this present study.

There were additional findings that linked the muscle activity to a few performance variables. Lower GMax activity appeared to show increases in the peak RFD and max force. This is in agreement with the findings mentioned in the previous section that these variables could be improved by enhancing the hip mechanics, and that hip mechanics are enhanced by the BFem contributing with the GMax in generating work and power. It was also determined that tighter coupling between the peaks of activation for the lower limb extensor musculature may influence the peak RFR and max force. This implies that the quicker energy travels proximal to distal through the linkage the more beneficial in attaining a higher takeoff velocity.

Although, we are suggesting specific roles of the musculature it is not recommended that muscle isolation be the focus in training regiments that aim to improve jumping performance. Instead, ensure that the musculature have the ability to appropriately contribute to their joint mechanics, and integrate this into the appropriate movement strategy.

6.3. Lumbar spine and hip mechanics

In agreement with the hypothesis there was a negative association between the lumbar spine and hip velocities. Although, this shows how the lumbar spine couples with the hip, maximizing the hip velocity at takeoff does not appear to have any influence on the vertical jump height. Therefore, this study investigated spine stability as a factor for improving jumping performance.

A stable spine could better resist perturbations, may improve transfer of energy between the upper and lower body segments, and act as a fixed point for the lower body to act on. Unfortunately, there is no direct measure of spine stability, but higher trunk activity may indicate greater stiffness therefore enhancing stability. Higher trunk muscle activity did occur in this study and this appeared to be positively linked to the vertical jump height and max force. Additionally, this study documented that tighter coupling between the peak activation of the trunk muscles was positively related to the max force, and this tighter coupling has been shown to enhance spine stiffness (Brown and McGill, 2009).

A consistent observation was made that all participants had peak activation of the trunk musculature in and around takeoff, but the coupling of these peaks were variant between participants. The synchronous activation of the trunk muscles (as shown in Figure 22(A)) was also observed in athletes performing plyometric push-ups, in which the trunk muscles were skilfully activated in a coordinated manner (Freeman et al., 2006). The result of simultaneous activation is that greater multidirectional stiffness of the lumbar spine is created, because the muscles of the abdominal wall and rectus abdominis are bound together by connecting fascia. This forms a composite, whereby the activity of each muscle augments the total stiffness (Brown and McGill, 2009). The higher level of spine stiffness ensures that the spine is stable, energy is not absorbed within the lumbo-pelvic articulation nearing takeoff and as a result takeoff velocity is maximized.

Limitations with these findings are associated with the possible issues with EMG normalization. Methods to combat these issues were described with detail in a previous section.

The practical significance is that higher spine stiffness likely benefits jumping performance and max force and can be achieved with higher peak activation of the trunk musculature. Synchronicity of the activation appears to be of importance and could further enhance stiffness. Therefore, coaches and trainers should challenge the trunk musculature to activate at high amplitudes but resist in attempting to achieve this through muscle isolation because this could disrupt the synchronicity needed for optimal stiffness. Instead, training should challenge the trunk muscles to activate simultaneously while limiting lumbar spine motion.

6.4. Links to injury prevention

Beyond some of the performance benefits that improved hip mechanics may offer, there may be additional benefits towards injury prevention, specifically patellar tendinopathy. Patellar tendinopathy has been described to be the result of excessive loading of the tendon (Khan et al., 2005). Patellar tendon compressive forces have been documented previously to increase as the knee flexion angle increases, with the rate of loading being maximum between 50-80^o (Escamilla et al., 2001). Additionally, the effect of jump strategy has been suggested to change the patellar tendon forces at takeoff and landing (Elvin et al., 2009). Therefore it appears that a possible way to prevent patellar tendinopathy in jumpers would be to encourage a strategy that reduces knee flexion angles, but sustains or improves jumping performance. The strategy used in our study to encourage hip dominance provides a possible solution in reducing high patellar tendon forces and torques.

6.5. Conclusion

There were multiple conclusions from this study. First, enhancing hip mechanics could benefit vertical jump performance, peak rate of force relaxation and peak rate of force development as revealed by the preferred jumping task analysis. However, the within-subject comparisons of the hip and knee dominant jumping tasks did not offer additional support for the importance of the hip. The novelty of the tasks and limited training time was possible rationale for the lack of support. Second, the mechanical outputs of the joints could be dependent on whether the bi-articular muscles are functioning to transfer or generate mechanical work and power. Third, the slowing of the lumbar spine appears to lead to a pulse in the hip at takeoff, but most importantly enhancing spine stiffness through higher trunk muscle activation and tighter coupling between the peaks near takeoff should benefit jumping performance.

Future investigations should focus on the factors that influence the hip and knee contributions in a jumping movement. This present study briefly documented that leg length may influence the hip and knee mechanics, but there may be additional anthropometric factors and these should be explored such as: pelvis size, acetabular depth and foot length. A better understanding of these anthropometric factors would allow trainers and coaches to determine those that are better suited for hip or knee dominant training. Modifiable variables such as arm swing has been shown to influence the lower limb work contributions (Hara et al., 2008) and thus varying arm swing strategies should be investigated. Similarly, the ankle contributes to the total work done (Hubley and Wells, 1983; Fukashiro and Komi, 1987) but varying ankle strategies should be further examined. Once these factors are better understood, then more comprehensive training protocols can be established and the effects of extended training times can be examined. The amount of training time needed to change a strategy without it reverting back to the previous over learned strategy will likely differ between individuals. Some individuals may be better at learning different strategies than others. Training the hip and knee dominant strategies until trial to trial variability is minimal would provide more or less support for enhanced hip mechanics.

6.6. Implications for training

The following suggestions are being made to guide those that develop training protocols to enhance jumping performance:

- Peak rate of force relaxation, max force and peak rate of force development must be maximized and may be done so by encouraging hip dominance with training protocols used in this study
- Athletes with longer legs may be better suited for hip dominant training, while those with shorter legs should consider knee dominant training
- Trained or present jumping strategy should be practiced to optimize control and improve performance
- Trunk muscles should be challenged to activate with higher magnitude and synchronicity

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Appendices

Appendix 1

The peak muscle activation (%MVC) for muscles of the trunk and lower limb for the preferred jumping task.

	Peak Muscle Activity (%MVC)															
Subject	REO	LEO	RIO	LIO	RRA	RUES	RRFem	LRFem	LGMax	RGMax	LBFem	RBFem	LVLat	RVLat	LGas	RGas
1	21.0	15.3	69.8	30.0	28.5	61.8	105.8	105.1	37.2	55.0	42.5	48.5	73.8	97.1	74.6	106.6
2	74.6	70.2	84.2	109.0	22.7	53.5	101.6	167.0	92.7	61.9	62.5	35.8	435.6	154.0	151.2	169.8
3	9.5	17.0	160.3	72.8	18.3	47.1	76.7	71.4	88.0	64.1	67.5	185.0	257.8	129.4	144.4	119.4
4	58.5	21.2	98.3	98.1	44.2	122.5	175.4	245.6	61.0	109.5	184.4	102.3	267.3	178.4	225.5	232.3
5	51.7	92.4	34.1	59.3	28.6	60.6	78.4	69.2	39.4	36.5	79.7	77.4	205.3	269.4	71.5	70.8
6	29.6	17.8	73.7	51.0	19.3	89.5	112.3	197.2	128.8	180.3	120.6	122.7	265.0	230.6	133.4	143.5
7	-	-	-	-	-	-	-	-	105.7	109.0	157.8	106.6	127.3	211.2	101.5	123.0
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	24.3	13.8	95.5	93.6	11.3	53.1	95.5	114.7	53.3	46.3	44.5	36.9	87.2	95.4	66.6	85.1
10	46.2	89.0	123.9	104.5	32.3	79.2	135.7	141.3	101.9	91.8	118.9	74.5	223.6	189.5	190.5	192.1
11	31.0	28.3	86.2	46.1	64.6	50.6	92.3	55.1	47.5	83.2	91.4	34.1	203.8	192.1	111.2	130.7
12	32.8	15.1	97.8	97.8	8.3	54.1	112.4	119.2	83.7	117.6	91.3	49.4	149.6	250.1	151.9	120.5
13	51.4	63.2	70.9	48.9	23.4	36.6	87.4	104.6	85.0	98.0	18.2	13.9	142.6	162.8	120.0	76.0
14	48.5	62.5	101.8	83.5	33.9	101.4	97.8	107.4	70.3	53.3	122.7	55.3	109.7	165.6	61.4	88.2
15	42.8	27.6	36.0	107.0	34.6	80.7	96.3	73.6	33.5	53.9	26.5	37.1	137.6	204.6	120.2	99.0
16	20.3	9.9	34.3	19.5	11.5	-	-	-	114.7	115.3	39.3	24.4	220.4	193.8	118.7	114.3
17	21.9	23.0	140.8	87.8	48.4	77.9	146.5	87.9	91.8	82.1	21.6	14.2	208.9	146.9	151.9	153.4
18	-	-	-	99.9	12.5	76.4	118.0	43.3	48.4	111.0	44.8	60.5	210.6	196.5	177.9	223.0
19	20.7	25.2	99.1	94.3	17.4	70.1	120.4	150.2	47.1	44.9	38.3	25.2	137.1	121.4	95.1	75.6
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-