Do East Asians Achieve Greater Knee Flexion than Caucasian North Americans, and are East Asian Kneeling and Squatting Styles Kinetically Different from North American Norms?

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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Helen C. Chong

Abstract

High flexion postures (specifically, kneeling and squatting) are used with greater regularity in East Asian (Chinese, Japanese, Korean, and Vietnamese) cultures for many activities of daily living (ADL). Furthermore, the favored style of kneeling and squatting is different between ethnicities: Caucasians typically flex their forefoot while kneeling and squatting, whereas East Asians tend to keep the top or bottom of the foot flat to the ground. Most, but not all, research suggests that East Asians are able to achieve a greater knee flexion angle during high flexion postures, but it is unknown if any differences between ethnicity extends to kinetic outcomes. A direct comparison between ethnicities with respect to kinetics has not been made. Where a difference in maximal attainable flexion angle exists, it is unclear whether the cause is cultural or innate. Therefore, this thesis project aimed to answer three related questions: 1) Do East Asian populations achieve a greater flexion angle than North American Caucasians; 2) If there is in fact a difference, is it a result of cultural upbringing or innate ability?; and, 3) Do different styles of kneeling and squatting alter the moments of force at the knee? To accomplish these aims, 43 participants were recruited from the University of Waterloo and fit into one of three groups: Caucasian, born and raised in North America (20 participants); East Asian, born and raised in North America (18 participants); or, East Asian, born in East Asia, living in North America for less than two years (five participants) (however, the East Asian born in East Asia group was excluded from statistical processing since the group size was considerably smaller). Kinetic, kinematic, neuromuscular, and passive range of motion data were collected and compared between different ethnicity groups.

East Asians did not achieve a greater mean knee flexion angle during kneeling compared to Caucasians (Canadian born East Asians=152.01° (±4.85°); Caucasians=153.07° (±7.46°), $p=0.2859$), but a greater mean flexion angle was found during squatting (Canadian born East Asians =147.96° (±6.62°); Caucasians = 141.69° (±17.48°), $p=0.0014$). Between Caucasians and Canadian born East Asians, there was also no difference in peak knee flexion angle during passive range of motion testing (Canadian born East Asians = 152.05° (±8.16°); Caucasians = 149.54° (±7.75°)), which indicates that there is no difference in ability to achieve greater high flexion between groups. Finally, it was found that different styles of squatting altered the kinetics at the knee, but different styles of kneeling were not significantly different. Flat foot squatting, a posture more commonly seen in East Asian cultures, had significantly ($p<0.05$) lower flexion and adduction moments at the knee than heels raised squatting (which is more commonly used by Caucasian North Americans) during descent, ascent, and static squatting. The mean static flexion moment (which is similar in magnitude to the peak flexion moment during descent and ascent) for flat foot squatting was 4.37 (±1.47) %BW*Ht, and for heels raised squatting was 5.99 (±1.84) %BW*Ht. The mean static frontal plane moment for flat foot squatting was -0.45 (±1.33) and for heels raised squatting was 0.59 (±1.02). (Negative values indicate an external abduction moment and positive values indicate an external adduction moment.) When performing high flexion postures, reduced knee moments are desirable since higher moments are associated with greater joint loading and injury risk.

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List of Abbreviations

%BW*Ht	Percent Body Weight Multiplied by Height
ADL	Activities of Daily Living
ASIS	Anterior Superior Iliac Crest
BMD	Bone Mineral Density
GCS	Global Coordinate System
GRF	Ground Reaction Force
LCS	Local Coordinate System
MCC	Maximal Calf Circumference
MTC	Maximal Thigh Circumference
MVIC	Maximal Voluntary Isometric Contraction
OA	Osteoarthritis
PROM	Passive Range of Motion
PSIS	Posterior Superior Iliac Crest
ROA	Radiographic Osteoarthritis
TKA	Total Knee Arthroplasty

1. Introduction

Kneeling, squatting, and crouching can collectively be called high knee flexion postures. East Asian cultures, including Chinese, Japanese, Korean, and Vietnamese nationalities regularly use high flexion for many activities of daily living (ADL). The Japanese culture in particular uses kneeling as a resting posture. Their tables are designed to be kneeled at, and chairs are very uncommon in most households - even in non-traditional households, people continue to kneel or sit on a *tatami* mat on the floor (Akagi, 2005). By having low tables, kneeling is used as a common posture during socialization. *Tatami* mats, essentially thick straw woven mats that lightly cushion the points of contact, ease discomfort that can occur in prolonged kneeling.

In Japan, the most common method of kneeling is a plantarflexed kneeling style (Mulholland & Wyss, 2001). The person kneels with shins flat to the ground and the instep of the foot on the ground. The bottom of the heels press into the buttocks. In North America, the most common style of kneeling is a dorsiflexed kneeling style, where the ball of the foot is pressed against the ground which lifts the heels up and results in the shin angling down to the knee. Depending on flexibility, a person may or may not be capable of making contact between buttocks and heels when resting in this posture.

The majority of Chinese households do not use kneeling for eating and drinking, but kneeling is used for ceremonial purposes and so is more commonly seen than in North American cultures. Chinese people also use a deep squatting posture for essentially all toileting in publicly accessed areas, and prefer to use a squat toilet as opposed to a seated toilet (when available), based on sanitary concerns around physical contact with the seated toilet (Cai & You, 1998). The general pose is a flat footed squat with the tailbone pointed to the ground, the knees approximately at shoulder level, and the feet positioned shoulder width apart.

The typical North American adult rarely engages in prolonged high flexion activities unless required by occupation or specific hobbies (such as gardening, or playing catcher position in baseball). In childhood, high flexion kneeling and crouching are very commonplace. However, by adulthood very few occupations or ADLs require high flexion. Children of most cultures are often seen squatting or kneeling while at play, but in most North American cultures, the practice of kneeling and squatting is less common by adolescent ages. In North America, the most common occupations to involve high flexion are construction workers, such as tilers or deckers, and childcare workers who frequently kneel in order to be closer to their small charges. For these occupations, the loss of high flexion can be an inconvenience at best, or a debilitating loss of livelihood at worst (Amin et al., 2008; Cooper, McAlindon, Coggon, Egger, & Dieppe, 1994; Jensen, Rytter, & Bonde, 2007).

Kneeling is very prevalent in many East Asian religions such as Buddhism, Shintoism, Taoism and Islam. The majority of Japanese identify themselves as Shinto, Buddhist, Christian, or some subset of all three (although it should be noted that the Christianity practiced in Asia has very different practices than are common in Europe and North America) (Kisala, 2006). China's major religions are Confucianism, Taoism, and Buddhism (*religiousfacts.com; accessed July 29, 2014).* Both countries also have undisclosed numbers of practitioners of 'folk' religions. Worship in Buddhist culture involves kneeling before an altar and placing the forehead to the ground, palms down beside the forehead. This motion is typically done once a day, but in times of increased religious fervor (such as pilgrimages or religious holidays) this number can increase to every altar passed. High knee flexion postures are also seen in Taoism and Shinto (Taoism uses

Tai-chi as a form of expression, and Shinto practices involve kneeling at altars using similar postures to Buddhism). Koreans also use a high flexion bow as a form of worship and ceremonial respect. In showing respect or appreciation to elders or other important community members, practitioners prostrate themselves before the respected person and kneel in a plantarflexed style, finishing by hinging forward at the hips and pressing the forehead and arms to the ground.

It is currently unclear whether East Asian populations can achieve a greater flexion angle in the knee than those of Caucasian descents. Some studies have found no significant differences (Leszko, Hovinga, Lerner, Komistek, & Mahfouz, 2011) whereas others have found that East Asians typically achieve approximately 20° greater flexion than Caucasians (Ahlberg, Moussa, & Al-Nahdi, 1988; Freeman & Pinskerova, 2003; Hemmerich, Brown, Smith, Marthandam, & Wyss, 2006). From these studies, it was demonstrated that Caucasian weight bearing high flexion angles are approximately 140° and East Asians can achieve approximately 160°. Those studies that have found a greater high flexion angle were unable to conclude whether this difference is cultural in nature or anthropometric. Additionally, there have been no kinetic analyses of East Asian styles of kneeling (plantarflexed kneeling) or squatting (flat foot squatting); this information would be helpful in designing more appropriate total knee arthroplasties (TKA) which are able to accommodate the varied moments of force at a greater range of motion. Therefore, this thesis project aims to answer three related questions: 1) Do East Asian populations achieve a greater flexion angle than North American Caucasians; 2) If there is in fact a difference, is it a result of cultural upbringing or innate ability?; and, 3) Do different styles of kneeling and squatting alter the moments of force at the knee?

2. Literature Review

2.1 Prevalence of high flexion postures in different cultures: a review

East Asian populations use high flexion postures in many different ADLs. These ADLs include eating, socializing, and religious or traditional ceremonies (Akagi, 2005). According to Mulholland & Wyss (2001), the most common postures are kneeling in the plantarflexed kneeling position (including a modified plantarflexed kneeling where one leg is raised so that the one knee is approximately level with the face), sitting cross legged, and squatting. These postures are all unconstrained by equipment such as chairs, which results in many different movements that may be displayed by people using these postures. Therefore, is it important to note that a certain level of variability amongst postures is unavoidable, especially during transitions into and out of the postures (hereafter referred to as descent and ascent). Figure 2.1 shows some of the more common variations of the two most used postures, based on descriptions from Mulholland & Wyss (2001).

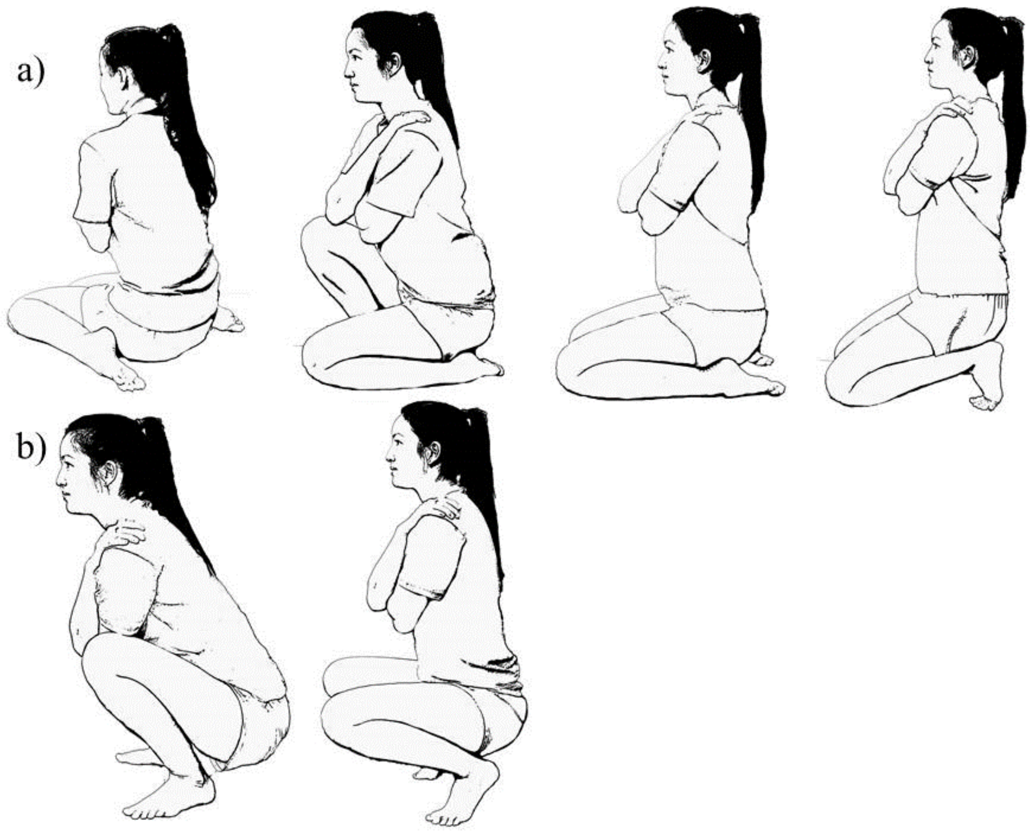


Figure 2.1 Common variants of (a) kneeling and (b) squatting based on descriptions from Mulholland & Wyss (2001)

Takano et al. (2008) state that Japanese people frequently use the plantarflexed kneeling posture as an alternative to sitting in a chair. They note that this posture is integral for continuing a traditional lifestyle, which is desirable for many people but especially older populations. Based on work by Das, Balasubramaniam, & Bose (1994), who examined different squatting postures in elderly and young Chinese adults, it appears as though high flexion postures are extremely relevant to an elderly population, but still very important to most young adults. They note that it was more common for Chinese people to squat in full flexion with their ischial tuberosity slightly raised from the ground, but that some people may prefer to rest the ischial tuberosity on the ground. Additionally, Das et al. (1994) underline the importance of squatting positions among Chinese people during “prayer, occupations and habit”. In a kinematic analysis of Chinese activities of daily living, the postures chosen were walking, jogging, and high flexion squatting, which highlights the importance of a flat foot high flexion squat within a Chinese population (Han, Cheng, & Xu, 2015).

In Western cultures (European and North American), not only is kneeling less common in adult ADLs, but kneeling styles differ from East Asian cultures. Western cultures are not based around kneeling- the vast majority of households have a kitchen table and chairs, a couch or sofa for relaxation, and the most common religion (Christianity) does not require frequent high flexion kneeling for worship. (Catholic prayer has the hips raised so that the knee flexion angle is approximately 90°.) It is estimated that approximately 80% of adults living in the United States and Canada are Christian (Pew Research Center, 2007; Statistics Canada, *accessed August 12, 2014*), with the next biggest religion being “no religion”. There are, of course, exceptions to the generalization that very few adults regularly engage in prolonged high flexion postures - some specific occupations such as flooring construction workers and childcare workers require repetitive and prolonged high flexion postures. Occupational kneelers in Western cultures have increased risk and prevalence of knee osteoarthritis (knee OA) (Coggon, Croft, Kellingray, Barrett, McLaren, & Cooper, 2000), which is not always consistent with East Asian literature. Chokkhanchitchai et al. (2010) found that extreme exposure to kneeling (kneeling for at least 5 minutes 17 times per day) resulted in decreased diagnoses of knee OA in comparison to other Thai people who kneeled with less frequency.

The importance of studying high flexion postures in an East Asian population cannot be understated - high flexion is undoubtedly an ADL. At present, there is a requirement for a greater depth of biomechanical knowledge and understanding in order to better support an East Asian lifestyle. Currently, differences in East Asian methods and requirements to achieve high flexion have not been well characterized. By analyzing differences between ethnicities, any differences if present will be a platform from which more ethnicity specific research can be modeled. Furthermore, a difference in high flexion moments about the knee as a result of an innate ability could be used to improve existing TKA designs by better emulating a healthy knee joint. The outcome measures with respect to required knee joint angles and the associated moments could be used to alter the testing protocols of current TKA designs, which are currently not required to reach full flexion. A difference in high flexion technique used by East Asians which results in a lower adduction moment may also be used as a recommendation to other ethnicities as a method to reduce potential joint degradation as a result of excessive medial loading.

2.2 Anthropometric data for East Asians and North American Caucasians

There are many documented differences in anthropometrics between East Asians and Caucasians which may contribute to different abilities to achieve high flexion postures (indicating that differences in knee flexion are innate). Primarily, it has been found that East Asian people have a smaller body mass than Caucasians (Liang et al., 2007; Nam et al., 2013; Russell-Aulet, Want, Thornton, & Pierson, 1993), but a higher bone mineral density (BMD) when adjusted for body size (Finkelstein et al., 2002; Liang et al., 2007; Russell-Aulet, 1993), and a higher body fat percentage (Lakshmi et al., 2012). However, this finding has not been replicated by all- Nam et al., 2013 found that Asians have a lower BMD, and postulate that this is the result of a lower body mass, which results in less skeletal loading and a lower BMD.

Kagawa, Binns, & Hills, (2007) compared Japanese and Australian Caucasians. They found that there was a significant difference between waist circumference and BMD, but that there was no difference in the sum of skin folds measuring % body fat. This result was echoed by

Lakshmi et al. (2012) who found that although Asians have a smaller body mass, they have a higher % body fat than Caucasian counterparts. Along with a smaller body mass, it has also been demonstrated by Liang et al. (2007) that Asians have a lower leg strength in comparison to Caucasians.

In a study by Yue et al. (2009), Chinese and Caucasian North American knees were compared for anthropometric information. Forty Chinese participants (male and female) were recruited from Shanghai Jiaotong University School of Medicine, and 36 Caucasian participants (male and female) were recruited from the Massachusetts General Hospital. Participants did not differ for general characteristics significantly by ethnicity, with the exception that white participants were younger than Chinese participants and Caucasian males weighed significantly more than Chinese males (females had no differences in weight). All knees analyzed were free of soft tissue abnormalities and free of knee OA, as was verified by computer tomographic (CT) images or magnetic resonance imaging (MRI). It was found that the Chinese participants in general had significantly smaller knees than their Caucasian counterparts. This includes both the femoral anterioposterior and femoral mediolateral directions, but the tibial sizes varied by sex. In females, the tibial dimensions were not significantly different, but in males, the tibial dimension was smaller than that of Caucasian males.

These findings were further supported by Vaidya, Ranawat, Aroojis, & Laud (2000) in a study which examined total knee arthroplasty (TKA) surgeries in Asian populations. Vaidya et al. found that more than 60% of the females who underwent a CT scan (26 women, 52 knees) had knees too small to fit the smallest size of femoral components available (55 mm). Component oversizing results in joint misalignment and subsequent issues at the knee. Iorio et al. (2007) found that Japanese people who had received TKA had less post-operative high flexion at the knee than Caucasian North Americans who had received the same treatments, and postulated that it was a result of poorly fitting devices (over-sized and not ethnically specific). A loss in high flexion is a documented leading cause for refusing TKA in Asian cultures (it is a possibility that refusal as a result of poverty is an undocumented cause), which in turn results in untreated knee OA that causes pain and debilitation (Akagi, 2005; Villar, Solomon & Rangam, 1989).

2.3 Knee osteoarthritis and total knee arthroplasty

Knee OA is a degenerative disease of the cartilage where the articular surfaces of the femur and/or tibia degrade, potentially causing pain and decreases in mobility. There are many different proposed mechanisms of how this disease is initiated and how it progresses; the purpose of this section is to discuss how high flexion activities, occupations, and difference in cultural aspects influence the prevalence of knee OA and what treatments are available. Based on work by Coggon et al. in 2000, occupational kneeling increases the risk of developing knee OA. Coggon et al. analyzed 518 pairs of participants (matched through sex and age): one person who had signs of knee OA (as determined by medical records) and one who had no preexisting knee damage. Participants were interviewed to determine possible causes of knee OA development and it was concluded that occupational kneeling (typically >1 hour/ day, although self-reported times should be considered estimates only) results in an increased likelihood of developing knee OA. Furthermore, it was concluded that a greater correlation was found when occupational kneeling was combined with carrying loads of greater than 25 kg on a regular basis. This finding was initially proposed by Cooper et al. in 1994, but the early findings were limited; the strongest conclusion by Cooper et al. was that weight bearing and prolonged kneeling may increase the risk of knee OA. The subsequent work by Coggon et al. (2000) confirmed this finding and suggested that occupational kneeling alone may also be a cause of knee OA. Coggon et al.

carried out the occupational knee bending study using a Western population, located in Southampton, England. Habitual kneeling may contribute to the initiation and progression of knee OA through both chronic and acute mechanisms, corresponding to both static kneeling and the dynamic transitions between standing and kneeling. Static high flexion postures are of interest with respect to kinematics and kinetics because joint angles that deviate from neutral could indicate poor joint congruency (and thus, alterations in loading of structures within the knee) and higher medial knee loading is associated with knee OA initiation and progression (Baliunas et al., 2002). Transitions into and out of high flexion may result in higher peak knee moments than during static high flexion, which is problematic since an increased moment of force about the knee has been associated with greater injury risk potentially resulting in kneeing mediated knee OA (Porter, Pollard, & Redfern, 2011).

There have been suggestions that East Asians have a greater prevalence of knee OA, possibly as a result of greater time spent in high flexion postures (Zhang et al., 2001; Zhang et al., 2004). In these papers by Zhang et al., the focus was on elderly Chinese people who use a flat footed squatting pose. The comparison was made to similar aged Caucasians living in the United States. However, it has also been suggested that the constant and extreme exposure of high flexion actually results in fewer cases of knee OA (Chokkhanchitchai et al., 2010).

That study (Chokkhanchitchai et al., 2010) involved an elderly Thai population (N=303, ≥ 50 years of age) who lived in the same area, were of the same ethnicity, but had different religious practices. One group were Buddhists, who prayed by kneeling and bowing their heads to the floor once per day. In contrast, the second group of Muslims was required to pray five times daily, which amounted to kneeling at least 17 times per day. In addition, it was noted that Muslims in this study required their children to begin practicing at approximately 5 years of age, whereas Buddhist adherents were less stringent for the age at which practitioners must begin (normally, it is more common to begin around the onset of puberty). Aside from religion, the greatest difference in high flexion lifestyle differences was the use of squat toilets: 81% of Muslims used an Eastern-style squat toilet in their home compared to 45% of Buddhists. Based on self-reported high flexion frequency, Muslims engaged in high flexion with a greater regularity than Buddhists living in the same area.

The Muslim population in this area, who had greater high flexion exposure for both religious practice and ADLs, had consistently lower rates of knee OA (radiographic knee OA and symptomatic knee OA); they also reported lower rates of general knee pain. The authors concluded that the likely cause of this disparity was the frequency of kneeling from a young age, which may have led “to a stronger knee infrastructure”. Additionally, moving from kneeling to standing many times a day may also improve the quadriceps muscle strength, which in turn decreases the prevalence of knee OA (Szoeke, Dennerstein, Guthrie, Clark, & Cicuttini, 2006). It is worth noting that the overall number of people who had reported cases of knee OA in the Thai population used was considerably higher than generally reported prevalence in Western societies (78% of the population had radiographic knee OA (ROA) compared to 28% ROA in a Western Culture (Jordan et al. 2007)). This apparently high prevalence of knee OA in the Thai population is supported in a study by Tangtrakulwanich, Geater, & Chongsuvivatwong, (2006) on the prevalence of knee OA in Thai monks, and so appears to be a realistic rate. It therefore appears as though kneeling mediated knee OA prevalence can be represented by a negative parabolic relationship: To an unknown point, increased frequency of high flexion postures increases the likelihood of developing kneeling mediated knee OA; there is, however, a decrease in likelihood of developing kneeling mediated knee OA under extreme exposure from a young age. This proposed relationship based on work from Chokkhanchichai et al. (2010) and Coggon et al. (2000) is illustrated in Figure 2.2.

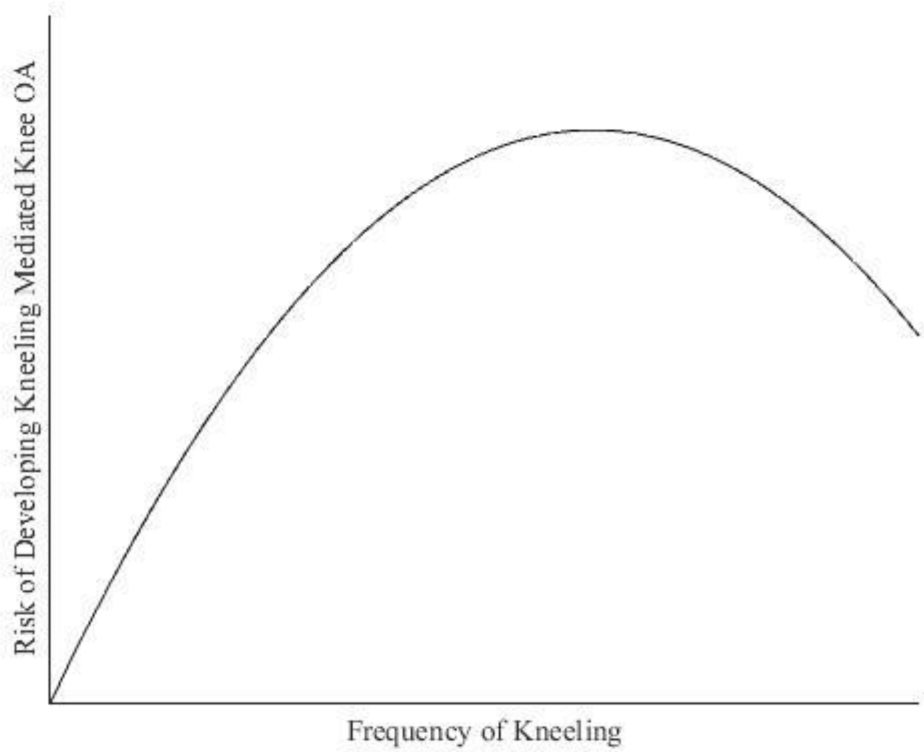


Figure 2.2 Proposed relationship between frequency of kneeling and the risk of developing kneeling mediated knee OA.

Das et al., (1994) examined 30 individuals in three different age ranges for hip OA. They conclusively showed that the elderly population who squatted on a regular basis (>6 hours/day) had “pristine” hips in comparison to those who didn’t squat regularly - they attributed this finding to more even loading leading to greater support in the hip sourcil. It seems reasonable then that the findings by Chokkanchichai et al. (2010) follow a similar premise and extreme exposure and practice of high flexion postures may help to prevent knee OA.

Given these contradictory theories, it is impossible to make any strong conclusions with regards to the prevalence of knee OA and its association with high flexion postures. Additionally, it is very difficult to make conclusions with regards to Chinese prevalence of knee OA, predominately due to the inability to assess patients. Approximately half (46.6%) of the population (total population=1.365 billion; *data.worldbank.org-accessed July 22, 2014*) lives in a rural setting, which results in undiagnosed and unreported illnesses. For comparison, 6.3 million Canadians (total population= 35 million), or l8%, live in rural areas; it is therefore expected that reported cases (mostly from urban settings) are much higher.

Further complicating the process of determining prevalence in Asian populations is the tendency to refuse total knee arthroplasty (TKA) on the premise that they do not achieve a great enough high flexion angle (Akagi, 2005; Dennis, Komistek, Stiehl, Walker, & Dennis, 1998; Villar, Solomon, & Rangam, 1989). This refusal of surgery results in reported numbers (when available) being skewed as it appears that Asian populations have far fewer severe cases of knee OA since fewer surgeries are carried out. Historically, the limited range of motion in TKA may have been true - earlier models only report approximately 120° full flexion under participant initiated crouching (no information is available with kneeling studies) (Anouchi et al., 1996). According to Akagi (2005), due to the untested nature of kneeling tasks, doctors are required to inform potential TKA candidates that they may never be able to resume their traditional way of life. In a study by Villa, Solomon, & Rangam (1989) it was noted that "many [of our] patients were offered surgery, but when told that they could not be guaranteed full flexion after the procedure, [they] refused further treatment". As recently as 2006, Hemmerich et al. concluded that TKAs that were available did not adequately meet the needs of Asian recipients for achieving a full range of flexion required to complete typical ADLs.

More recently, TKA designs are being built to accommodate an Eastern lifestyle which includes the ability to continue with high flexion ADLs (Acker, Cockburn, Krevolin, Li, Tarabachi & Wyss, 2011). However, it has not yet been demonstrated that the improved TKA has increased the prevalence of doctors actually performing the surgery in Asia. This could be a result of a lack of information conveying newer results, and excess costs associated with TKA initially. Per capita (on an annual basis), Chinese people spend on average 320 USD on health care personally, compared to an average of 4676 USD for Canadian citizens (World Health Organization, *accessed August 14, 2014*). This discrepancy suggests that far fewer Chinese people regularly attend health clinics in order to be diagnosed with knee OA and do not pay to have TKAs on a regular basis.

Overall, the actual prevalence of knee OA and subsequent need for TKA in East Asian populations is difficult to accurately estimate. Given that North Americans and East Asians have different styles of high flexion kneeling and squatting (generally, North Americans use a flexed foot pose while East Asians do not), and the incidences of kneeling and squatting are not well known, a biomechanical analysis comparing the different styles of kneeling and squatting would be beneficial. The comparison between styles would reveal whether one style of kneeling/squatting uses mechanics more likely to lead to knee OA. The current information is conflicting with regards to whether increased incidences of high flexion lead to, or deter from, knee OA.

2.4 Existing work in kinematics of high flexion postures

Hemmerich et al. (2006) conducted a study examining the kinematics of the hip, knee, and ankle in high flexion postures. They used a non-Western culture (Indian men and women) to evaluate flat foot squatting, heels raised squatting, plantarflexed kneeling, dorsiflexed kneeling, and sitting cross legged. All five of these poses were considered to be ADLs (and were comfortable to the patients for five minutes or longer), but only people who personally used each specific pose daily performed the task. Therefore, each person was very experienced at each pose that was recorded. Due to very open interpretation of tasks, high flexion was not achieved for the majority of kneeling styles (instead of sitting back on the heels, participants kept the torso in line with the thighs, resulting in approximately 90° knee flexion angles); high flexion was achieved for squatting styles. The mean full flexion angles recorded for the knee were 152° ± 7° in heels raised squatting and 152° ± 11° for flat foot squatting. These angles are considerably higher than reported by Flanagan, Salem, Wang, Sanker, & Greendale (2003) of 101° ± 21° for an older Western population. The discrepancy between high flexion angles was suggested to be a result of an older age in the Western participants, a higher BMI, and less familiarity with the task.

Hefzy, Kelly & Cooke (1998) also evaluated the kinematics of high flexion postures. Using just 5 participants (all of Arabic descent), the knee flexion angles were observed while completing a mock prayer routine. The participants began in a plantarflexed kneeling-like position, with the feet plantar-flexed and the buttocks resting on the heels. They then tilted forward to an intermediate position (approximately 120° of knee flexion), and then all the way into a bowed position with the forearms and forehead resting on the ground and the buttocks raised (where knee flexion was approximately 90°). It was demonstrated that the starting position began with high flexion between 150° and 165°, which is a greater knee flexion angle than is recorded for most Western Caucasians (approximately 140°) (Rooas & Anderson, 1982).

Han, Cheng, & Xu (2015) completed a kinematic analysis of the lower extremities in a healthy Chinese population during walking, jogging, and deep squatting. The study aimed to compare males and females during these activities of daily living, and it was concluded that during deep squatting, differences in knee angle were only present in the frontal and transverse planes. This is in contrast to many Western publications, where it is often found that Caucasian females are able to obtain a greater flexion angle than Caucasian males (Leszko, Hovinga, Lerner, Komistek, & Mahfouz, 2011). Finally, it was concluded that the flexion range of motion required for the flat foot squat was greater than was previously reported by a Western journal (146˚ reported by Han et al., versus 101˚ reported by Flanagan et al. (2003) in a Western population. However, the comparison was drawn from an older adult population.).

In a study by Leszko et al. (2011) a direct comparison was made between Japanese and North American Caucasians. They concluded that there was no difference of knee flexion angle between ethnicities during high flexion between women, but that Japanese men achieved a greater high flexion angle than Caucasian men. When sex was ignored however, they concluded that there is no difference in ability to achieve a greater high flexion angle between ethnicities. The next closest example is a study done by Ahlberg et al. (1988) which emulated the experimental protocol by Rooas & Anderson in 1982. Rooas & Anderson studied a Caucasian population (Scandinavian) while Ahlberg et al. studied Saudi Arabians. It was concluded that Saudi Arabians can achieve significantly greater high flexion knee angles than Scandinavians (159.6°±8.5° vs. 143.8°±6.5°, respectively). However, without a direct comparison being made it is impossible to control for other external factors. By examining studies that involve different populations, it is possible to get a reasonable overview of the maximal high flexion angles achievable, but a study where the methods and criterion are identical would be beneficial to the existing literature (such as was done by Leszko et al., (2011) for kinematic variables). Table 2.1 summarizes the existing literature on knee flexion angles during maximal high flexion postures.

Table 2.1

High flexion knee angles from various studies including Caucasian Westerners and Asians

Author	**Year**	**Ethnicity**	**Knee Full Flexion (°)**	**Standard Deviation (°)**
Acker et al.	2011	Middle Eastern	141.6	8.3
Ahlberg, Moussa, Al-Nahdi	1988	Saudi Arabian	159.6	8.5
Flanagan et al.	2003	Caucasian	101	21
Hefzy, Kelly & Cooke	1998	Saudi Arabian	157.3	4.9
Han, Cheng, & Xu	2015	Chinese	150.9	10.7
Hemmerich et al.	2006	Indian: Dorsiflexed kneeling	154	8.6
		Indian: Plantarflexed kneeling	144.4	13.2
Leszko et al.	2011	Japanese	152.4	7.1
		Caucasian North American	148.8	8.1
Nagura et al.	2002	Caucasian North American	150	
Roaas & Andersson	1982	Scandinavian	143.8	6.5
Zhou et al.	2012	Chinese	146.1	10.4

2.5 Existing work in kinetics of high flexion postures

A gap exists in the literature regarding kinetic analysis of high flexion postures. Kinematic information (which will be used for verifying the kinematics found in this study) has been documented, but the kinetics of high flexion postures have not been well reported. Dahlkvist, Mayo & Seedhom (1982) performed a two-dimensional modeling analysis of the joint and muscle forces surrounding the knee for 6 male participants during a squatting activity. They found that the normal tibio-femoral force is typically 5 times body weight, and the tangential tibio-femoral force is typically 3 times body weight. Additionally, greater forces in both normal and tangential directions were associated with the downwards transition in comparison to the upwards transition. Directly measured values from Kutzner et al. (2010) were lower in the knee than those previously reported by Dahlkvist et al. (1982); during self-selected angles of squatting, the peak flexion moment was on average 3.16% BW*Ht (body weight times height).

Pollard, Porter & Redfern (2011) also analyzed the kinetics of the squat, and a “near full” flexion bilateral kneeling condition. The kneeling condition used a flexed foot pose; no plantarflexed kneeling pose was analyzed. During squatting, the flexion moment at the tibia reached approximately 5 % BW*Ht which was significantly more than the flexion moment seen during the near full kneeling pose (approximately 2.5 % BW*Ht). Squatting produced a higher moment of force in the knee in the varus direction (an external knee adduction moment) and internal rotation in comparison to the near full kneeling pose, but in those directions the moment of force was more similar between the two styles (<1 times body weight for varus moments, and approximately 0.5 % BW*Ht for internal rotation moments), compared to the sagittal plane moments. The authors therefore concluded that squatting “is likely to be the most detrimental high-flexion posture” since a reduction in moments on the knee is assumed to reduce the risk of injury.

Nagura, Matsumoto, Kiriyama, Chaudhari, & Andriacchi, (2002) also completed a kinetic analysis of high flexion postures - in this case, double support and single support kneeling were compared. The kneeling styles had no specific reference to deliberate postural considerations for the foot, alluding to the possibility that participants knelt as desired. Nagura et al. (2002) found that the highest flexion moments were seen when the participants exceeded 140° knee flexion, where moments were approximately 10 % BW*Ht. This large net quadriceps moment was accompanied by a net positive posterior force at the knee during high flexion. This study chose to stop transitional data collection at the point where the knee made contact with the ground; however, subsequent work by Chong, Tennant, Kingston & Acker (submitted) has indicated that, for some people, the peak flexion moment may occur once the participant is in full flexion (essentially, static kneeling).

This thesis work discerns differences between Western (dorsiflexed kneeling and heels raised squatting) and East Asian (plantarflexed kneeling and flat foot squatting) styles of kneeling and squatting, specifically whether one type of kneeling or squatting may result in lower moments of force at the knee. Lower moments of force are desirable because they may decrease the likelihood of joint injury (Pollard et al., 2011). Increased adduction and decreased flexion moments at the knee are associated with an increased incidence of knee OA (Baliunas et al., 2002; Deluzio & Astephen, 2007; Jackson et al., 2004); therefore, a comparison between kneeling styles focusing specifically at the adduction and flexion moments is beneficial. In an occupational setting, these findings could then be used to make postural recommendations to limit deterioration at the joint. For traditional or religious settings, any potential findings might have negligible effect on behavioral changes in the general population; for those with existing health issues however, medical guidance can be used to alter the traditional pose to a more joint saving posture.

2.6 Passive Range of Motion

Passive range of motion (PROM) is a measure of a person's full range of motion with no muscular intervention on their part. It determines the end range of motion, as defined by passive structures (bone on bone interactions, connective tissues), as opposed to an end range of motion that may be determined by active structures (such as tight muscles, although an active end range of motion could also be dependent on bone on bone interactions). For high flexion postures, a participant's range of motion may contribute to their ease of performing a given pose with respect to how much flexion can be achieved in the ankles, knees and hips. Therefore, a measure of a participants PROM is valuable to determine if the pose is limited by passive structures or perhaps muscular activity.

A concept related to PROM is joint laxity, which is used to assess the ligamentous properties of a joint as opposed to the full range of motion relating to all of the passive structures (amongst which ligaments may provide an end range). In 2009, Hovinga & Lerner demonstrated the differences in joint laxity between Japanese and Caucasian populations in the knee joint. They studied 70 healthy adults (47 Caucasians and 23 Japanese) of similar age and height (BMI differed; the Japanese participants collectively had lower BMIs in comparison to Caucasians) and assessed ACL laxity using a MEDmetric (San Diego, CA) KT-1000 arthrometer. The device measured tibial displacement relative to the femur during a manual drawer test performed until there were 3 consistent values by the same examiner. It was found in this study that the Japanese had consistently greater laxity than the Caucasian counterparts (Japanese: Females 8.1 ± 0.65 mm & Males 6.9 ± 0.56 mm; Caucasian: Females 6.4 ± 0.37 mm & Males 4.9 ± 0.35 mm). With a relatively small sample size, Hovinga & Lerner (2009) concluded that the differences in laxity at the knee "may be due to increases in high flexion activities in Japanese or possible genetic differences".

The findings of Hovinga & Learner (2009), coupled with the related concept of PROM, make PROM of particular interest to this study because joint laxity is exceptionally difficult to accurately measure without specific equipment and professional training (at the knee, an arthrometer is typically used for an anterior drawer test of ACL laxity as a measure of knee joint laxity. However, an anterior drawer test may not be indicative of knee joint laxity in high flexion postures.). PROM may help to clarify any potentially confounding effects of thigh/calf circumference - a larger circumference will lead to a smaller maximum flexion angle as the soft tissues will collide earlier. This might lead to the conclusion that East Asians have a greater high flexion angle because they typically have smaller bodies (Liang et al., 2007; Nam et al., 2013; Russel-Aulet, 1993). Kneeling and squatting are generally expected to be passive poses at the end range of motion since the weight of the body should be resting on the ligaments. However, it is possible that some people would not be able to reach a ligamentous end range of motion- instead, they would be relying on muscular activation (which can be measured through the use of EMG on specific thigh muscles) to maintain the pose. Based on general anthropometrics from East Asian populations and Caucasians, it could be expected that Caucasians have larger thigh and calf circumferences, which could possibly translate into smaller maximal flexion angles and greater muscle activation. In this thesis work, the examination of PROM made it possible to determine if each ethnicity uses their full range of motion at the ankle, knee, and hip during each pose or if they are inhibited by muscular intervention (as seen through EMG activation and a maximum flexion angle during poses that is below the upper limit of the passive range of motion).

3. Purpose and Hypotheses

3.1 Purpose

There is both a primary and secondary objective of this research. The primary purpose of this study is threefold: First, to investigate the differences in maximum flexion angle between two styles of squatting and kneeling during kneeling and squatting between East Asians and Caucasian North Americans; second, to determine if any differences found are innate or the result of cultural upbringing based on a comparison of exposure to, and the maximum flexion angle exhibited during, kneeling and squatting between groups; and, third, to compare the kinetics between the squatting and kneeling styles typically seen in East Asian and Western cultures. The previous sections discussed the importance of high flexion to East Asian ADLs, as well as the differences between East Asian and Western styles of high flexion postures. To date, there have been no direct kinetic comparisons between East Asian and Caucasian North Americans during kneeling styles. Although joint moments have been calculated for dorsiflexed kneeling (Pollard et al., 2011) and kneeling with an unspecified foot posture (Nagura et al., 2002), these studies did not achieve full flexion (instead, Pollard et al. specified their protocol as “near full”) and did not analyze East Asian styles, specifically plantarflexed kneeling and flat footed squatting. There have also been no attempts to characterize whether any differences in high flexion postural kinetics and kinematics are cultural or innate.

The secondary objective of this research is to provide three-dimensional kinetic curves for moments at the knee during high flexion postures. There have been several kinematic studies which address the kinematic requirements of high flexion postures, but to date, none have published kinetic curves for either kneeling or squatting. By producing three-dimensional kinetic curves for two styles of kneeling and two styles of squatting, an existing gap in the literature of high flexion research will be filled.

This study will produce several novel outcomes:

- The moments of force about the knee during four different high flexion styles and the transitions into and out of the poses. In particular, the kinetics for the plantarflexed kneeling pose and flat footed squatting has not been reported. Moments are of particular interest because they are related to injury risk in high flexion postures (Pollard et al., 2011).
- A comparison between groups with different ethnicities to determine if maximum flexion is cultural or innate.
- A comparison between groups with different ethnicities to determine if the groups differ in passive range of motion, which may provide insight into differences of ability to achieve high flexion postures.

3.2 Hypotheses

The specific hypotheses to be tested in the proposed study were as follows:

1a) East Asians will achieve a greater knee flexion angle during all kneeling and squatting static tasks.

There is conflicting information regarding whether or not East Asians can obtain a greater high flexion angle than Westerners. The majority of studies have found greater angles (normally ~20° greater) but they are not direct comparisons (Ahlberg et al., 1988; Freeman & Pinskerova, 2003; Hemmerich et al., 2006**).** There is one direct comparison study, which did not find differences between Japanese and Caucasian participants during squatting (foot position was not defined or restricted) (Leszko et al., 2011).

1b) The differences in flexion angles will be innate, not cultural. Therefore, the group of East Asians raised in Canada will have a greater knee flexion angle than the Caucasian participants during high flexion postures, but will have similar scores on the Frequency of High Flexion questionnaire.

The majority of studies have found greater flexion angles in Asian participants than Western participants (Ahlberg et al., 1988; Freeman & Pinskerova, 2003; Hemmerich et al., 2006) but did not investigate whether these differences might potentially be an effect of innate ability (e.g. due to differences in body shape, bone size, or laxity) or frequency of high flexion during ADL.

2) East Asians will exhibit greater flexion PROM than Caucasians in the ankle, knee, and hip.

East Asians will exhibit greater flexion PROM than Caucasians at the ankle, knee, and hip, potentially as a result of greater joint laxity (Hovinga & Lerner, 2009). Although ligament laxity will not be directly measured, the passive range of motion will provide insight into the individual's sagittal plane rotational laxity. While in a high flexion posture, an individual with greater joint laxity in the knee could reach a greater knee flexion angle with the applied force of the individual's body weight. Since it is expected that East Asians will achieve a greater flexion angle at the knee during high flexion, a possible factor may be a difference in joint laxity between ethnicities.

3a) Plantarflexed kneeling and flat foot squatting will have lower moments of force at the knee in the sagittal plane (flexion moment) than dorsiflexed kneeling and heels raised squatting, respectively, during static holds.

Plantarflexed kneeling and flat foot squatting will have lower moments of force at the knee in the sagittal plane compared to dorsiflexed kneeling and heels raised squatting, respectively, because the ground reaction force during flat foot squatting will be translated posteriorly compared to heels raised squatting, resulting in a decreased moment arm. Plantarflexed kneeling may have a lower moment of force at the knee compared to dorsiflexed kneeling because a greater portion of the participant's weight will be distributed over the participant's feet (assuming an increase in knee flexion angle as a result of the feet being plantarflexed instead of dorsiflexed, which results in heel-gluteus contact at a greater knee flexion angle), increasing the moment at the ankle. This will increase the sagittal plane moment at the knee, assuming all other factors are consistent between styles of squatting.

3b) Plantarflexed kneeling and flat foot squatting kneeling and squatting will have a higher peak moment of force in the frontal plane than dorsiflexed kneeling and heels raised squatting, respectively, during downwards and upwards transitions.

Peak adduction moment will be higher for the transitions associated with the plantarflexed kneeling as a result of differences in moment with respect to flexion angle: Higher knee moments have been associated with higher flexion angles, after approximately 60° knee flexion (Dahlkvist et al., 1982). Therefore, the expected increase in maximum flexion angle during plantarflexed kneeling and flat foot squatting will correspond with a higher adduction moment in plantarflexed kneeling and flat foot squatting high flexion poses. A higher external knee adduction moment is associated with increased medial loading (Lewek et al., 2004).

Previous research has proposed that higher adduction moments in the knee joint may influence cartilage morphology and knee OA initiation (Andriacchi & Mündermann, 2006; Baliunas et al., 2002; Miyazaki et al., 2002).

4. Methods

4.1 Experimental Protocol

4.1.1 Participants, recruitment and screening

Forty-three students from the University of Waterloo were recruited for this study: 20 male and 23 female, between the ages of 19-32 years. Participants were recruited to fit into one of three categories: Caucasian, raised in North America (hereafter called Caucasian), East Asian, raised in North America (hereafter called Canadian East Asian, or CEA), or East Asian, raised in East Asia. Participant characteristics can be found in Table 4.1. The majority of the two raised in North America groups were born in Canada; however the group also contained four participants who moved to North America before they were three years of age, and one who moved at age five. The raised in East Asia group had been living in Canada between 15 months and four years. One female participant had been living in Canada for 13 years, but self-identified as raised in East Asia and so was considered East Asian, raised in East Asia for grouping purposes.

Table 4.1

Participant characteristics presented as mean (±SD) for each group.

Group	n	Sex	Age (years)	Mass (kg)	Height (m)	MTC (cm)	MSC (cm)
Caucasian	10	Male	22.8 (1.93)	72.95 (14.30)	1.73 (0.07)	54.04 (6.41)	36.81 (3.49)
	10	Female	23.7 (1.77)	63.84 (6.19)	1.66 (0.03)	52.83 (5.45)	36.20 (2.30)
Canadian East Asian	10	Male	20 (0.81)	69.9 (8.97)	1.72 (0.06)	50.88 (3.82)	36.58 (3.06)
	8	Female	19.75 (1.03)	57.6 (5.52)	1.57 (0.05)	51.4 (4.62)	35.40 (2.33)
East Asian, Raised in	2	Male	24 (0)	52.7 (5.09)	1.79 (2.33)	52.7 (5.09)	39.70 (6.08)
East Asia	3	Female	24.3 (6.81)	48.5(2.21)	1.61 (9.71)	48.50 (2.20)	35.97 (1.31)

Note: MTC (Maximal Thigh Circumference); MSC (Maximal Shank Circumference)

Participants were excluded if they had sustained any knee injuries within the last three years that resulted in greater than three days off of work/school, or any knee injuries that required surgery. Participants were also asked if they experienced knee pain from kneeling or squatting, and to participate, were required to report that they did not experience knee pain on a regular basis. Finally, pregnant women were excluded since pregnancy can increase the participant's ligamentous laxity which may alter the PROM of the participant (Dumas & Reid, 1997).

4.1.2 Study protocol.

4.1.2.1 Experimental set-up

Electromyography, kinematic, and kinetic data were collected for this study. All raw signals were collected using First Principles software (version 1.2.3). Electromyography (EMG) was collected using a wireless system (Wave Plus EMG, Cometa, Cisliano, Italy) and was sampled at 2048 Hz with a built-in bandpass filter of 10-500 Hz. Electrodes were placed bilaterally on the rectus femoris, biceps femoris, gluteus medius, tibialis anterior, and the lateral gastrocnemius. Ground electrodes are not required with this EMG system. All electrodes sites were shaved with a disposable single-use razor, exfoliated, then cleaned with rubbing alcohol, and allowed to dry before the electrode application. Surface electrodes (Ambu Blue Sensor N, Denmark) were placed according to SENIAM guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000) with an interelectrode distance of 2 cm (De Luca, 1997). The experimenter who placed the electrodes was consistent throughout the entire experiment.

Kinematic data were collected using an 18-camera Optotrak motion capture system (Northern Digital Inc., Waterloo, ON, Canada) at a sampling rate of 64 Hz. Registration of the capture volume was performed during a 65 s trial using a rigid cube with 16 infrared markers. Alignment of the global coordinate system (GCS) was completed using a 4 marker digitizing probe. The three points used to define the GCS were the origin (offset from the corner of force plate 4), a point along the positive x axis (offset from the corner of force plate 2) and a point on the x-z plane (the upper-left hand corner of force plate 1). Figure 4.1 shows a diagram of the Biomechanics of Human Motion laboratory set up (BOHM lab).

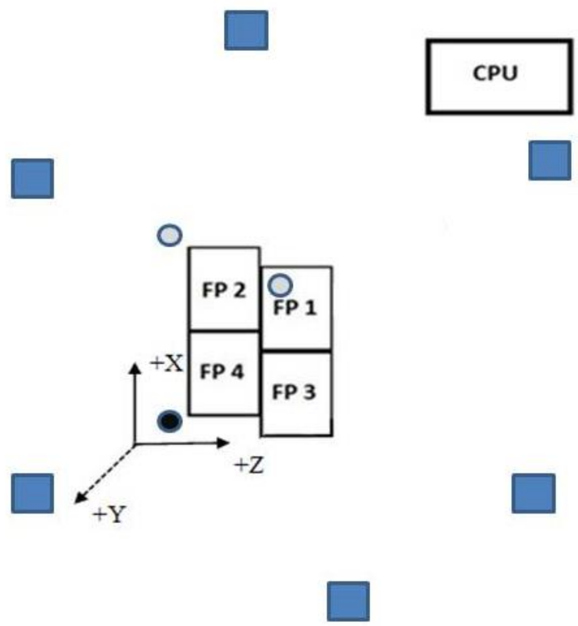


Figure 4.1 BOHM lab set up. The positive XYZ coordinate system represents the GCS, where the Y axis is perpendicular to the ground. A black circle represents the origin, and the two grey circles represent the digitized points used to define the positive x axis and the x-z plane. Cameras are represented by blue squares.

Infrared marker clusters were placed bilaterally on the feet, shanks, thighs, and a pelvic fin, and were secured using medical grade adhesive (3M, Michigan USA) and elastic Velcro® straps. For specific parts of the data collection (passive range of motion testing of ankle and hip scour testing), participants were required to be supine- therefore, the pelvic fin could not be used for these trials and instead 2 additional rigid body clusters were placed inferior to the iliac crest on the left and right side of the pelvis. The clusters were equipped with 5 infrared (iRed) emitting markers (3 markers were required to make a plane and the 4^{th} and 5^{th} accounted for drop out or obstruction due to the movements) with the exception of the barefoot markers, which had 4 iRed markers. Anatomic landmarks were digitized using the 4 iRed digitizing probe. The digitized landmarks were bilateral and as follows: With respect to the pelvic fin marker cluster and the temporary left and right pelvis markers when present- anterior superior iliac spine, iliac crest, posterior superior iliac spine; with respect to the thigh clusters- greater trochanter, medial femoral epicondyle, lateral femoral epicondyle; with respect to the shank cluster- medial tibial plateau, lateral tibial plateau, medial malleolus, lateral malleolus; with respect to the foot cluster- medial malleolus, lateral malleolus, head of first metatarsal and head of fifth metatarsal, heel, and toe. Figure 4.2 shows a diagram of the participant instrumentation, including marker clusters and EMG electrodes.

Kinetic data was collected using four AMTI force platforms (Advanced Mechanical Technology Inc. Watertown, MA, USA) at a sampling rate of 2048 Hz. Force plate amplifiers were turned on a minimum of 6 hours before data collection and were zeroed prior to use once the participant arrived. The force plate corners were digitized using the 4 marker probe and subsequently used for transformations between the force plate coordinate systems and GCS.

4.1.2.2 Experimental protocol.

Participants arrived at the BOHM lab which is located in Burt Matthews Hall room 1405 at the University of Waterloo, Waterloo, ON. Street shoes were removed immediately upon entering the laboratory and were not used for the duration of the experiment. All data was collected with the participant barefoot. The participant was given a brief tour of the lab with an explanation of the equipment that was used. The participant then changed into comfortable shorts and a t-shirt, which were provided by the participant. The participant was then asked to read and sign an informed consent form.

The participant then filled out a short questionnaire (Frequency of High Flexion; found in Appendix A) which outlines the frequency with which they kneel and also some general background questions. The participants who were born and raised in East Asia answered the same questions twice; the first time with respect to their lives while living in East Asia, and the second set of questions with respect to their time spent living in Canada. The reason for this duplication of answers is that although it is generally agreed that the majority of cartilage and bone morphology is established in childhood (Ballabriga, 2000), there is a possibility that a complete change in lifestyle will alter the participants cartilaginous deposits (Van Ginckel et al., 2010). Following the questionnaire, demographics and anthropometrics were collected. The participants' sex, age, height and weight were recorded, along with the maximal and distal femoral condyle thigh circumference and maximal and proximal tibial condyle calf circumference.

The participant was then outfitted for EMG collection as outlined in the experimental set-up section. The participant was asked to perform isolated muscle contractions to ensure correct placement on the bulk of the muscle (Kendall, McCreary, & Provance, 1993). Maximal voluntary isometric contractions (MVICs) were then performed for the relevant muscles for normalization purposes (Burden, Trew, & Baltzopoulos, 2003). Participants completed two reps of MVIC per muscle group, with at least 1 minute rest between each MVIC for a given muscle group. Gluteus medius MVIC was conducted with the participant laying on their side, and performing a clamshell movement with their legs while the experimenter manually resisted. The hamstrings were manually resisted while the participant lay prone with their knee at approximately 55° flexion. Tibialis anterior was manually resisted as the participant sat upright and attempted to point their hallux over their ipsilateral shoulder, moving only at the ankle (SENIAM guidelines; Hermens et al., 2000). The quadriceps were resisted by machine while the participant was seated with their knee at approximately 35° flexion. The participant then attempted to extend their leg in against weight resistance. The gastrocnemii were also machine resisted using a leg press. The participant was seated with their foot in plantarflexion, and then applied pressure to their forefoot against weighted resistance (SENIAM guidelines; Hermens et al., 2000). Data was collected for six seconds per trial which allowed for a relaxed start and end. Participants were given verbal encouragement throughout the trial and to ensure maximal effort is put forth to obtain the best possible maximal muscle activation (Lewek et al., 2004). Following the MVIC collections, participants were asked to lay supine and relax completely to collect a six second baseline trial (a trial of the muscles at rest).

Following MVIC collections, the participant was outfitted with kinematic clusters as described in the experimental set-up section. The dual pelvis cluster set up was used first for passive range of motion testing. After the clusters were all secured to the participant, a 5 second standing reference trial was taken; the participant stood with their arms crossed at chest level, and feet shoulder width apart. The static standing reference trial was required for standard model reconstruction. Participants then completed a ‘hip-swing’ trial on both the left and right legs (trials will last for 25 seconds each) in order to find the functional joint center of the hip and ‘knee-extension’ trial on both the left and right legs (20 seconds each) to find the functional joint center of the knee (Begon, Monnet & Lacouture, 2007). For the hip-swing trials, participants were asked to flex, extend, abduct, adduct, and circumduct the hip joint- a chair was used for balance at the participant's side if needed. The movement of the thigh relative to the trunk was then used for computing the functional joint. For the knee-extension trials the participant flexed and extended the knee at a consistent rate through a range of knee joint angles between ~0° flexion and ~90° flexion. The movement of the shank relative to the thigh was then used for computing the functional joint.

Figure 4.2 Participant instrumentation; grey bars on the lateral aspect of limbs represent rigid body marker clusters with the markers facing laterally (pelvic fin is central), and the 4-marker foot clusters are shown on the dorsal aspect of the foot - they wrap around the foot towards the lateral side to avoid being obscured during kneeling. Pairs of yellow circles represent placement of EMG electrodes.

Passive range of motion (PROM) hip scouring was the first PROM measure taken. The participant was instructed to lie supine on the massage table and relax completely. The experimenter then cradled the participant's shank so that the participant had their hip approximately 90˚ flexed and their knee 90˚ flexed. The experimenter reminded the participant to relax, and then scoured the acetabulum by driving the knee towards the chest and swinging the knee from side to side around the shape of the acetabulum. The trial lasted for 10 seconds, and at least 2 repetitions were taken. The experimenter felt for resistance and the assistant experimenter checked the trials for muscular activation level- once both the experimenter and assistant agreed that the trial was less than ~10% MVIC, the trial was considered "good" and a second trial taken. Both the right and left hips were tested.

Next, ankle PROM was tested. The participant remained supine with one leg resting in a custom jig that held the knee at 30˚ (shown in Appendix B, Figure B.1) (Roaas & Andersson, 1982). The experimenter applied even force throughout the participants' full range of motion (as indicated by the participant using a Chatillon CSD200 Dynamometer (AMETEK Inc., Berwyn, PA) to determine the maximal force applied. The dynamometer was applied 15 cm from the lateral malleolus along the foot (typically at approximately the heads of the metatarsals) perpendicular to the foot surface. At least two passive trials were taken for both the right and left ankles.

The two pelvis marker clusters were then removed and replaced with a single pelvis fin. The pelvis landmarks were then re-digitized, and then hip-swing trials were redone to reflect the new pelvis cluster. No other re-digitization was required since no other clusters were moved. Finally, knee PROM was tested. The participant was instructed to lay prone on the massage table and the experimenter held the shank to move the leg into full passive flexion (so that the participant's heel made contact with the gluteus maximus if possible), using a Chatillon CSD200 Dynamometer to determine the maximal force applied. The dynamometer was applied 30 cm from the lateral tibial plateau along the shank perpendicular to the anterior shank surface.

Finally, participants were shown four consistent images of the four poses they were to perform (Figure 4.3). The participants were given a minimum of two practice trials per pose, but were encouraged to take more practice if they felt uncomfortable with the protocol. Very few participants chose to continue with their practice (<10 participants), but those who did require more practice generally chose to practice the flat foot squat.

All poses were performed on the force plates. The kneeling poses had each foot and knee on different force plates, and the force plates were covered with 4 separate foam yoga mats which compress to a negligible thickness under load. These mats are similar in purpose to the *tatami* mats used in traditional Japanese households and help to increase the realism of the experiment as very few people kneel on hard surfaces with no padding. Furthermore, the thin yoga mats were cut to the size of the force plates and were not attached to one another- this helped to prevent shear forces that were not due to knee contact from being applied to the plates.

The participants were required to use an asymmetric unilateral transition approach for the kneeling poses. The participant began standing off of the force plates, and was instructed to step forward when they felt ready to begin. Most of the participants then stepped forward with their trail leg onto a near force plate, and then took an additional step with their lead leg onto the farther force plate before lowering their body so that the trail knee made contact with the force plate (Figure 4.4). After the initial step forward, some participants chose to take an additional step with their lead leg, so that their feet were side-by-side on the close plate. They then stepped forward again with their lead leg, before kneeling down in the asymmetric pattern requested. The participant then held the pose in high flexion for 8 seconds, and then moved into the ascending transition. For the ascent, the participant stepped forward with their lead leg, the raised themselves up from the kneeling position and stepped backwards off of the force plates. The participants were permitted to use whichever leg they chose for their lead leg based on the initial practice sessions; however, they were required to use the same lead leg for the entirety of the data collection.

a)

Plantarflexed Kneeling: The instep of the foot is in contact with the ground, and the buttocks rest on the heels of the feet. The torso is upright, and the head is facing frontwards.

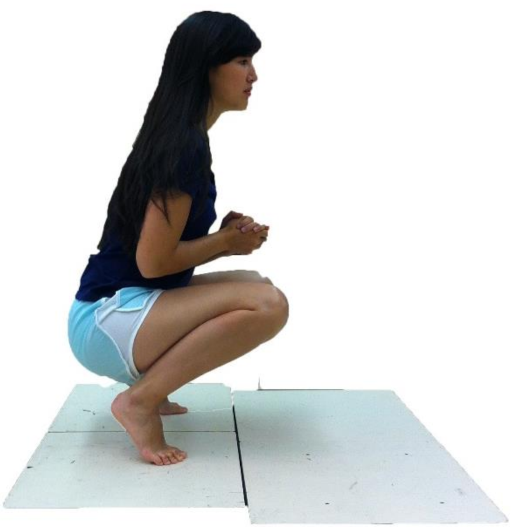
b)

Dorsiflexed Kneeling: The forefoot is flexed so that the head of the metatarsals and the plantar aspect of the toes are in contact with the ground. The buttocks rest on the heels.

c)

Flat Foot Squat: The feet are flat on the ground at approximately shoulder width. The knees are close to the shoulders and the tailbone is pointed to the ground.

d)



Heels Raised Squat: Similar pose to the flat foot squat, with the heels raised up so that only the forefoot is in contact with the ground.

Figure 4.3 The four photographs that each participant was shown to demonstrate the styles they were asked to complete.

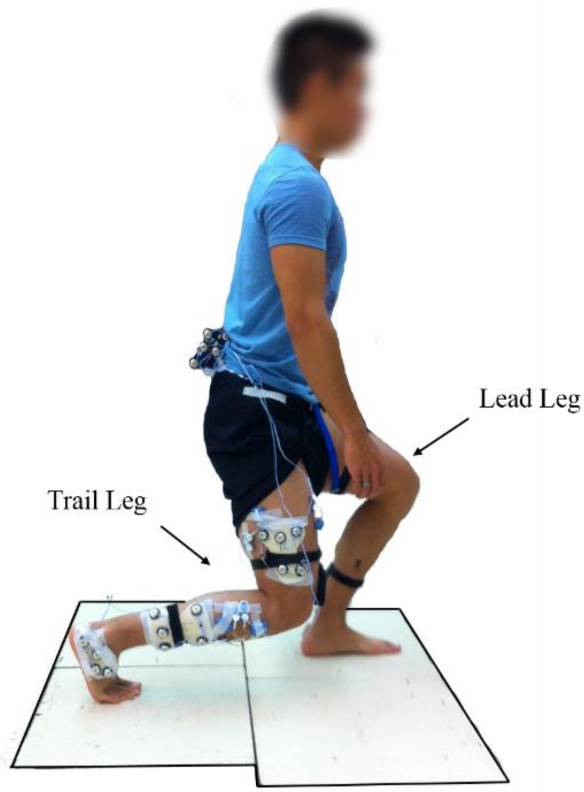


Figure 4.4 Participant during a descending transition. In this example, the left leg is the lead leg, and the right leg is the trail leg.

For the squatting poses, participants started off of the force plates, and then stepped forward with either leg. They then stepped onto the second force plate with their opposite foot and squatted to full flexion. Participants then held the pose for 8 seconds as the static hold, and then straightened their legs and stepped backward off the force plates, completing the ascending transition.

Participants completed 5 trials for each of the four different styles of high flexion, which were randomized between styles by a random number generator. A trial was continuous between the descending transition, static hold, and ascending transition. A total of total of 20 trials were recorded from four styles (Figure 4.3) and five trials each.

4.2 Data processing

Kinematic, kinetic, and EMG data was processed using custom Matlab (Mathworks, Inc., Natick, MA) code and Visual 3D (C-Motion Inc., Germantown, MD) pipelines in order to obtain the dependent variables. Kinematic and kinetic raw data was filtered with a dual pass 2nd order Butterworth filter with a 6 Hz cut off frequency (Wells & Winter, 1980). The global coordinate system was set in accordance with Wu et al. (2002) and was maintained for the assignment of local coordinate systems (LCS) to each segment. All LCSs were created by defining the axial (+Y) vector, creating a YZ plane with a lateral anatomical marker (specified in section 4.1.2.1 Experimental Set-Up and illustrated in Table 4.2), projecting the anterior/posterior axis (+X) anteriorly from the YZ plane, and then crossing vectors X and Y to create axis +Z.

The knee and hip LCS have origins based on the functional joint trials that were collected for each participant. The functional movement trials, which required the participant to move through all possible planes of movement at each joint, were used to create a helical joint center which is the point at which no movement of the proximal segment occurs relative to the distal segment during motion (Schwartz & Rozumalski, 2005). At the left and right hips, this single point helical joint center was used as the origin for the LCS. At the left and right knees, the knee is treated as a single degree of freedom joint for the purposes of analyzing the function knee joint center, and so a functional joint axis is created instead of a joint center. The lateral and medial femoral condyles were then projected onto the functional joint axis (http://www.c-motion.com/v3dwiki/index.php/Functional_Joints, C-Motion Wiki Documentation*; accessed December 17, 2015*).

Joint angles and internal joint moments were calculated using Visual 3D and moments were normalized to each participant with percent body weight times height (%BW*Ht). Each joint moment was expressed in the proximal segment, with the exception of the knee joints which were expressed in the tibial coordinate system (Mündermann, Dyrby, Hurwitz, Sharma, & Andriacchi, 2004). The knee joint moment was expressed in the tibial coordinate system to interpret the flexion moment about the mediolateral axis of the tibia, not the mediolateral axis of the thigh. However, with the exception of the knee, joint moments are more commonly expressed in the proximal segment, which is what was chosen for the ankle and hip moments. Visual 3D always follows a right-hand rule for calculating joint angles and moments, and reports net internal joint moments. In order to maintain symmetry within the right and left legs, as well as consistency between joints for positive results, the following transformations took place following the right-hand rule convention: Left ankle, negate moments about the tibial Y and Z axes; right ankle, no transformation; left knee, negate X, Y and Z axes; right knee, negate moments about the tibial X axis; left hip, negate moments about the pelvis Y and Z axes; right hip, no transformation. This sequence resulted in positive flexion (dorsiflexion at the ankle), adduction, and internal rotation for all external joint moments. During kneeling, an additional ground reaction force (GRF) was added into the kinetic rigid link model once the knee was in contact with the force plate. This additional GRF was applied to the segment closest to the GRF, which in all cases of kneeling was the shank, at the location of the center of pressure of the GRF. The negated ankle joint moments and forces acting on the foot were used as the distal known forces moments acting on the shank for calculating the knee joint moment and forces along with the center of mass and distances to each known force. The GRF applied to the shank does not have an effect on the ankle joint moment or forces (http://www.c-motion.com/v3dwiki/index.php/Force_Assignment, C-Motion Wiki Documentation; *accessed December 17*, *2015*).

During PROM testing, the participant was required to lie supine, which prevented the use of the pelvic fin marker cluster to track pelvic movement. Instead, two 5-marker clusters were firmly attached to the participants' skin, just below the iliac crest on the left and right. Since this area is susceptible to soft tissue artifact, especially in postures where the hip is flexed such as while performing a passive hip scour trial, movement of the pelvis was recorded based on the marker cluster on the contralateral side relative to the testing leg. Since the leg that was not being scoured was flat on the massage table as the person lay supine, the soft tissue artifact issue was greatly reduced. Following the PROM trials, the left and right pelvis markers were removed and were replaced with the pelvis fin marker cluster on the skin covering the sacrum for pelvis segment motion tracking for the remainder of the experiment.

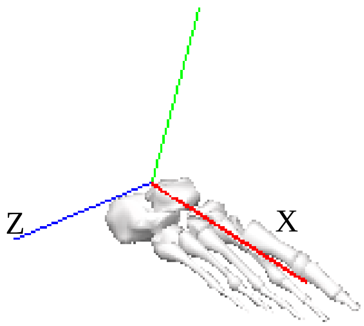
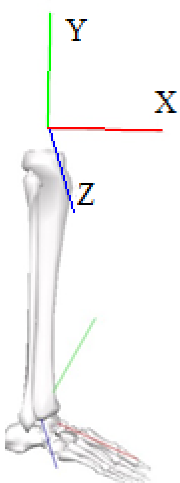
A kinematic pelvis segment was created for the purposes of calculating hip joint angles. The kinematicpelvis reduced the ~20˚ tilt that is inherent with the CODA pelvis coordinate system definition due to the fact that the CODA pelvis' transverse plane passes through the left and right PSIS and ASIS. The kinematic pelvis segment is aligned so that the standing reference trial is considered 0° hip flexion (the horizontal LCS axis is aligned to the horizontal GCS axis). The CODA pelvis definition was chosen, despite this limitation, because the ASIS and PSIS landmarks are fairly easy to palpate on most healthy participants. In contrast, the Visual 3D pelvis definition uses the left and right iliac crest, which can be less easy to palpate, and the greater trochanter, which is not a bony landmark of the pelvis but of the thigh. However, the Visual 3D pelvis is aligned to the global coordinate system and so does not need a virtual pelvis segment to be created.

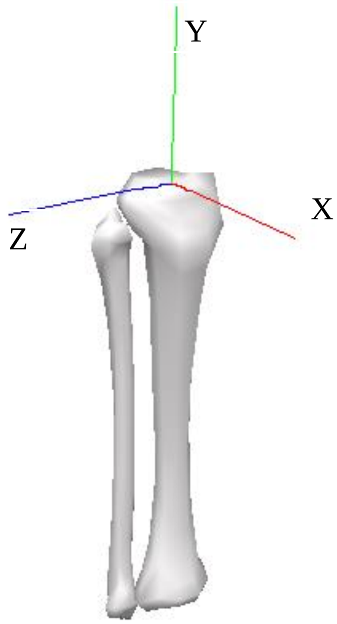
A kinematic foot segment was created for the purposes of calculating ankle joint angles, so that the ankle posture in neutral standing was considered to be 0˚ (dorsiflexion is positive, and plantarflexion is negative). This was done in order to better define dorsiflexion and plantarflexion. Without this virtual realignment, anatomical position would be considered a plantarflexed pose, since the X axis of the foot is defined as a vector from the midpoint of the first and fifth metatarsals and the midpoint of the lateral and medial malleolus. The kinematic foot and kinematic pelvis segments were used for kinematic calculations only. The kinetic calculations were based on the native segmental coordinate systems, described in Table 4.2. The native segments are built on each participant's anthropometrics and so use the participant specific lengths which are required for moment calculations.

The movement trials were set to a timer such that the participant could begin the descent movement at their leisure, though the data was clipped to begin when the participant made first contact with a force plate (exceeding a 10N threshold). The participant was required to be in the static pose 5 seconds later. The static pose was held for 8 seconds. The upward transition was unconstrained with respect to time, but the end of the transition was defined as the last instant of contact (no longer exerting a minimum of a 10N force) on the force plate; the trial ended when the participant stepped off the plate.

Table 4.2

Local coordinate system for the foot, shank, thigh, and pelvis

Segment	Description
	**Foot Segment (Kinetic Only)** Visual 3D automatically calculates the frontal plane using the end segment markers (the malleoli and metatarsals in this case). It then uses the created YZ plane to place the anterior X axis (parallel to the ground). However, in the case of the foot, the default plane created should be the transverse plane (XZ, not YZ). Therefore, the LCS is rotated to the shown configuration, so that the YZ plane is the frontal plane and the XZ plane is the transverse plane. Origin: Midpoint between lateral and medial malleoli YZ plane: Lateral and medial malleoli; 1st and 5th metatarsal Y axis: Vector through the midpoint of lateral and medial malleoli and 1st and 5th metatarsals. X axis: Perpendicular to the YZ plane, projecting anteriorly Z axis: Cross product of XY. Upon completion of the LCS, the LCS is rotated to match the shown configuration
	**Kinematic Foot Segment (Kinematic Only)** The virtual foot segment has the identical axis system to the tibial segment in the standing reference position (the coordinate system at the top of the figure to the left). However, the virtual foot is tracked to the actual foot markers so that standing in a neutral position is considered 0°. When the ankle moves through dorsiflexion, the foot markers move relative to the tibial coordinate system and result in a positive value. When the ankle moves through plantarflexion the foot markers move relative to the tibial coordinate system and result in a negative value for the sagittal plane ankle angle.



Tibial Segment

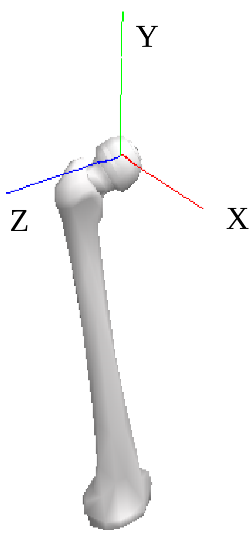
Origin: Midpoint between lateral and medial tibial plateaus, projected onto the lateral-medial axis of the functional knee joint center.

YZ plane: Lateral tibial pleateau and medial tibial pleateau, lateral and medial malleoli

Y axis: Vector bisecting the midpoints of the tibial pleateau and malleoli

X axis: Perpendicular to the YZ plane, projecting anteriorly

Z axis: Cross product of XY



Thigh Segment

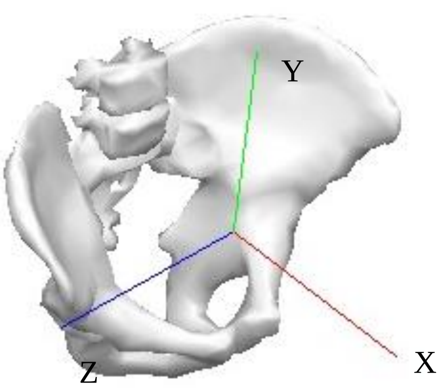
Origin: Functional hip joint center

YZ plane: Greater trochanter, lateral and medial femoral epicondyles

Y axis: A vector between the hip joint center and the midpoint of the femoral medial and lateral epicondyles

X axis: Perpendicular to the YZ plane, projecting anteriorly

Z axis: Cross product of XY



Pelvis Segment (Kinetic Only)

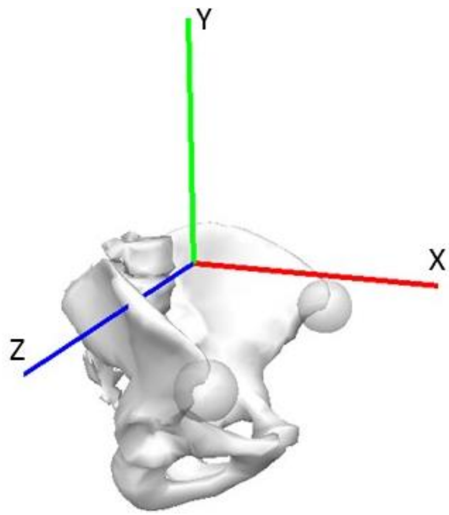
Origin: Midpoint between ASIS markers

XZ plane: Left and right ASIS and left and right PSIS

Y axis: Perpendicular to the XZ plane

Z axis: A vector from the origin towards right ASIS

X axis: Cross product of YZ



Kinematic Pelvis Segment (Kinematic Only)
Origin: Midpoint between projected iliac crest landmarks (based on the calculated functional hip joint centers)
Y axis: Projected vertically upward with respect to the global coordinate system
Z axis: Origin towards right iliac crest
X axis: Cross product of YZ

EMG raw data had the bias removed, and was then full-wave rectified and low-pass filtered at 6 Hz using a Butterworth filter (Winter, 1990). EMG was amplitude normalized to the maximum linear enveloped amplitude achieved during the MVIC collections. The main purpose of the EMG collection was to determine if static poses are passive in nature - therefore, there was minimal processing for the EMG data. To establish if muscles were active during poses, a threshold of 10% MVIC was be used. It has been found that ±5% MVIC is the threshold at which surface EMG can be accurately measured (De Luca, 1997), and 10% MVIC has been used as a passive threshold to ensure that no measurement errors were found (Rozzi, Lephart, Gear, & Fu, 1999). The number of participants in each group who had active muscles during the static poses was compared to the total number of participants in the group and contrasted between groups.

The PROM kinematic data were processed in the same method as the movement trial data using V3D. The maximal flexion angle was calculated from each joint (dorsiflexion and plantarflexion in the ankle, knee flexion, and hip flexion). The force transducer was used to ensure that the amount of force required to reach the end range of motion for each participant was similar, and the EMG data on the muscles was used to confirm that the testing was passive (<10% MVIC).

The questionnaire results were used to confirm (or disprove) the expected differences in lifestyle based on ethnicity. Reponses to each question were given a numerical value such that 0 was assigned to “never”, 0.5 to “less than once per week”, 1 to “at least once per week”, 2 to “daily”, and 3 to “more than twice daily”. The scores were then added up and participants were grouped based on score to determine if each group had different kneeling exposures on a day to day basis.

4.3 Statistical analysis

Statistical analysis was performed using SAS software (SAS Institute Inc., Cary, NC) version 12.1. Each hypothesis was tested separately, predominately using a 4-way analysis of variance (ANOVA). The East Asian raised in East Asia group was not included in statistical analysis; the recruited group was too small (5 participants) to give meaningful results in comparison to the much larger groups. The East Asian raised in East Asia group will be reported as case studies where appropriate. For clarity, the hypotheses from Section 3.2 are repeated here in an abbreviated format, followed by details of the statistical test used to test each hypothesis. Table 4.3 summarizes the potential factors for all of the subsequent hypotheses. The factors of sex and leg are not directly related to the hypotheses in this study. With respect to sex, there is a discrepancy between maximum flexion angle between males and females based on ethnicity. Caucasian males and females have exhibited a difference in maximum flexion angle (Leszko et al., 2011) but no difference in flexion angle between East Asian males and females has been found (Han, Cheng, & Xu, 2015). Therefore, a main effect of sex was explored to determine if this difference persisted in this specific population. A comparison of legs (lead and trail for kneeling, seen in Figure 4.4, and right and left for squatting) was carried out to ensure that the dependent variables of interest are not different based on which leg is chosen for analysis in future works.

Common variance was tested using the square root residuals for each treatment group; the common variance assumption of an ANOVA states that the variance between sample means is consistent. If the common variance assumption was violated, a modified Levene's test was used to establish a more appropriate p-value. Unless otherwise stated, all statistical tests were run using an alpha value of 0.05.

Interactions between all of the factors were be tested using the initial ANOVA. However, if no interactions were present, the interaction terms were dropped from the statistical model in order to improve model fit (only main effects were tested in the subsequent ANOVA) by increasing the variance explained by the model.

Table 4.3

4-way mixed model ANOVA factors

Factors	Factor levels
Ethnicity (between factor)	Canadian East Asian/ Caucasian
Sex (between factor)	Male / Female
Style (within factor)	Plantarflexed kneeling / Dorsiflexed kneeling
	OR
	Flat foot squat / Heels raised squat
Legs (within factor)	Lead/Trail
	OR
	Left / Right

4.3.1 Hypothesis 1: Comparing groups

1a) East Asians will achieve a greater knee flexion angle during kneeling and squatting, regardless of foot position.

To test this hypothesis, mean knee flexion angle during the static phases was analyzed using two mixed model ANOVAs, one for kneeling and one for squatting, described in Table 4.3 (all of the factors were used). It was expected that there would be a main effect for ethnic group, which would imply that one ethnic group is different from the other. A main effect for style was also expected - however, the interpretation of differences in mean flexion angle between styles would be simply that different poses may illicit different angles. Additionally, it was expected that there would be a main effect of sex, likely indicating that females are able to achieve a greater flexion angle than males during static poses.

1b) The difference in knee flexion angle (if found) will be innate, not cultural.

It was anticipated that a main effect of ethnicity for hypothesis 1a would indicate that the Caucasian group had significantly less flexion in comparison to the Canadian East Asian group. To interpret whether this result is a factor of innate ability or cultural upbringing, the Frequency of High Flexion questionnaire was used; the same score between groups would indicate that the result is innate, whereas a difference in score would indicate a cultural effect (differences in high flexion exposure).

4.3.2 Hypothesis 2: PROM

2) East Asians will exhibit greater flexion PROM than Caucasians in the ankle, knee, and hip.

Maximal flexion angle was averaged for each participant from the ankle (dorsiflexion and plantarflexion), knee, and hip. Four (two for the ankle, and one for the knee and hip) mixed model ANOVAs (no postural consideration from Table 4.3) were used to compare the maximal flexion range between ethnicities. It was expected that there would be a main effect of ethnicity, with the East Asians exhibiting a higher flexion range at all three joints. Additionally, it was expected that there would be a main effect of sex, with the post hoc tests indicating that females are able to achieve a greater flexion angle than males for all three joints.

4.3.3 Hypothesis 3: Comparing high flexion styles

3a) Plantarflexed kneeling and flat foot squatting will have lower moments of force at the knee in the sagittal plane (flexion moment) than dorsiflexed kneeling and heels raised squatting, respectively, during static holds.

To test this hypothesis, mean flexion moment during the static hold was tested using two mixed model ANOVAs (Table 4.3, all factors); one ANOVA compared the mean flexion moment between the two squatting styles while the second compared the mean flexion moment between the two kneeling styles during the static hold.

The mean flexion moment during static phases was analyzed because knee OA has been linked to both chronic and acute mechanisms (Coggon et al., 2000; Thambyah, Goh, & Das De, 2005; Zhang et al., 2004). The static phase during high flexion emulates a chronic joint exposure to high flexion; higher knee joint moments during static kneeling and squatting may increase the risk of developing kneeling mediated knee OA as a result of chronic exposure.

3b) Plantarflexed kneeling and flat foot squatting will have a higher peak moment of force in the frontal plane than dorsiflexed kneeling and heels raised squatting, respectively, during downwards and upwards transitions.

To test this hypothesis, the peak adduction moments from both legs were compared to result in a total of four mixed model ANOVAs, summarized in Table 4.4. The factors are summarized in Table 4.3. Peak adduction moments during transitions are of particular interest because knee OA has been associated with acute mechanisms during periods of increased joint loading (Thambyah, Goh, & Das De, 2005).

Table 4.4

Hypothesis 3b ANOVA summary

ANOVA Number	Style	Phase
1	Kneeling	Descending transition
2	Kneeling	Ascending transition
3	Squatting	Descending transition
4	Squatting	Ascending transition

A main effect for ethnicity would indicate that different ethnic groups exhibit different peak moments regardless of style, and a main effect for style would indicate that there was a difference in peak moment between the 2 different styles. An interaction, if present, between ethnicity and style would imply that certain ethnic groups may have a lower/higher peak moment only during specific styles of kneeling or squatting compared the other ethnic group. It was not anticipated that there would be an interaction.

5. Results

5.1 Hypotheses 1 and 2: Flexion Angle between Ethnicities

The mean knee flexion angle during static kneeling (Table 5.5) was significantly different between males (151.26 ± (6.91)) and females (154.00 ± (5.38)), p=0.0075. It was also significantly different between styles of kneeling (plantarflexed kneeling = 153.95 ± (5.53); dorsiflexed kneeling = 151.17 ± (6.85), p=0.0055). There were no significant effects based on ethnicity or right and left legs.

Figure 5.5 shows the mean knee flexion angle achieved by the Caucasian, Canadian East Asian and East Asian participants during static kneeling. Both sexes are averaged together since the main effect for kneeling styles indicated that the mean knee flexion angle was significantly different regardless of sex. Ethnicities are plotted separately since they are central to the hypothesis, and to show the results for the East Asian group, who were not included in the statistical analyses.

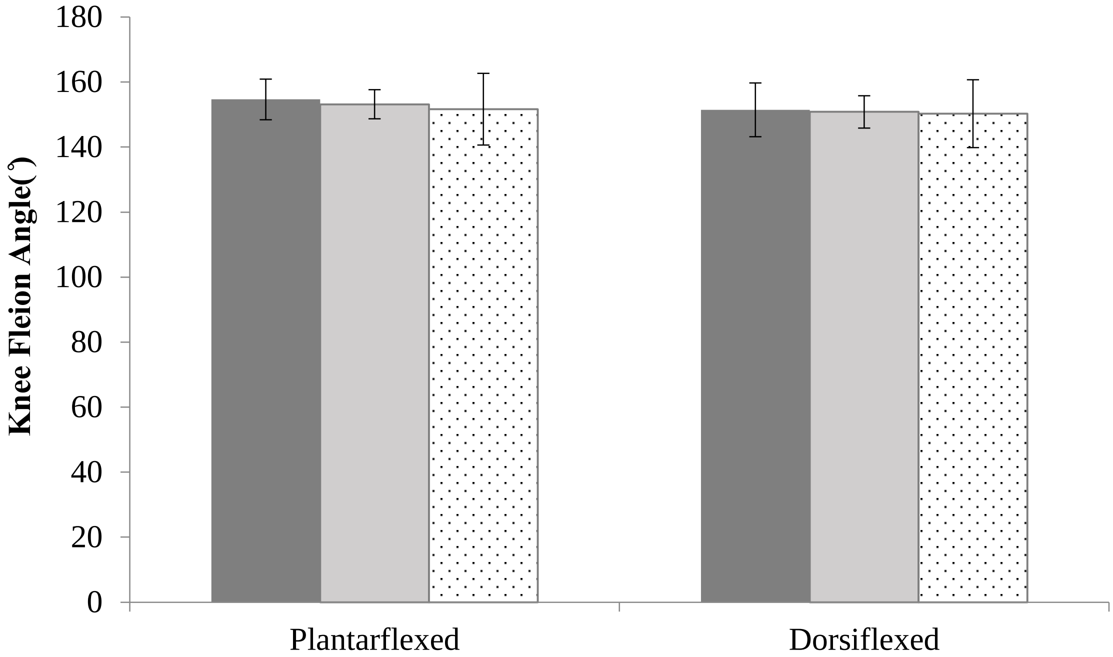


Figure 5.1 Mean knee flexion angle during static kneeling pose. Dark grey represents Caucasian (n=20), light grey represents Canadian born East Asians (n=18), and dots represents East Asian raised individuals (n=5). ±1SD is given for each group.

The mean knee flexion angle during static squatting (Table 5.6) was significantly different between Caucasians (141.69° ± (17.48°)) and Canadian East Asians(147.96° ± (6.62°)), p=0.0014. It was also significantly different between flat foot squatting (138.14° ± (15.82°)) and heels raised squatting (151.17° ± (6.86°)), p<0.0001. In Figure 5.6, sexes are averaged together since they are not significantly different during squatting, and the East Asian group has been included (also averaged between sexes, n=5).

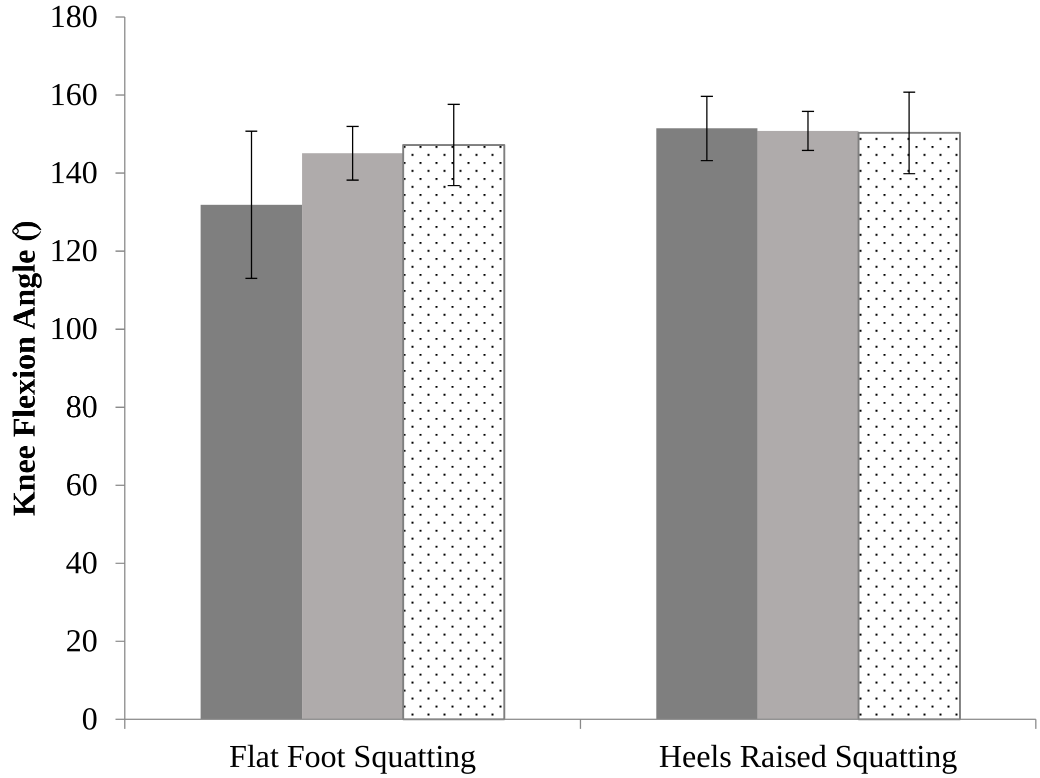


Figure 5.2 Mean knee flexion angle during static squatting pose, averaged between males and females. Black=Caucasian (n=20), grey=Canadian born East Asians (n=18), and dot=East Asian raised individuals (n=5). ±1SD is given for each group.

PROM data was collected to determine if participants utilized their full range of motion during the high flexion postures as well as to determine if the maximal flexion angle for each joint was different between ethnicities. There is a main effect of ethnicity for maximal dorsiflexion angle, where Caucasian maximal dorsiflexion angle is 13.91° (±5.91°) and Canadian East Asian maximal dorsiflexion angle is 21.63° (±5.35°). Maximal plantarflexion angle had a main effect for sex, where females have a significantly greater maximal plantarflexion angle (-31.66° (±7.97)) than males (-26.26° (±6.39°)). Finally, there was an interaction between ethnicity and sex for maximal hip flexion angle where males had a significantly lower hip flexion angle than females within the Caucasian group, but a significantly higher hip flexion angle for the Canadian East Asian group (summarized in Table 5.1). The maximal hip flexion angle also showed a main effect for ethnicity, where Caucasians had a significantly lower maximal hip flexion angle (124.97° (±9.21°)) than Canadian East Asians (129.91° (±7.30°)) despite the existing interaction between ethnicity and sex.

Table 5.1

Mean (± SD) PROM flexion angles (°) for the ankle, knee, and hip as a comparison between Caucasians and Canadian East Asians

	Caucasian		Canadian East Asian	
	Male	Female	Male	Female
Dorsiflexion ǂ p<0.0001	13.27 (5.91)	14.55 (5.04)	21.61 (5.35)	21.65 (5.52)
Plantarflexion * p=0.0022	-26.53 (7.53)	-32.09 (7.24)	-26.00 (5.20)	-31.11 (9.02)
Knee Flexion	148.77 (8.33)	150.32 (7.26)	153.84 (9.79)	149.81 (4.93)
Hip Flexion † p=0.0003, ǂ p=0.0069	120.87 (10.0)	128.75 (6.63)	131.97 (7.26)	127.61 (6.09)

ǂ Main effect of ethnicity
* Main effect of sex
† Interaction between ethnicity and sex

The Frequency of High Flexion questionnaire was designed to determine how often participants kneeled or squatted on a day to day basis. It included religious practices, occupational setting, use of high flexion for rest or comfort, as well as a self-determined number of hours daily spent kneeling or squatting (see Appendix A for more details). A numerical value, where 0 represents 'never' on the frequency response form and 3 represents 'more than twice per day' was then assigned to the responses. Table 5.2 shows the outcome sorted by ethnicity. Both the Caucasian and the Canadian East Asian groups answered the questionnaire only once, but the East Asian group answered the same questionnaire twice; the first time through with respect to living in East Asia and the second time through with respect to living in Canada. A two-tailed t-test was run on the cumulative frequency of kneeling scores of each participant, comparing the Caucasian and Canadian East Asian groups. There was no significant difference in frequency of kneeling scores (p=0.13) between these two groups. The East Asian group (which was excluded from statistical analysis) had higher minimum, maximum, and mean scores while living in East Asia, but appear to be culturally similar once they assumed a Canadian lifestyle based on outcome scores.

Table 5.2

Frequency of High Flexion questionnaire results for each ethnicity (Caucasian, Canadian born East Asian and East Asian). The minimum score, maximum score, and group mean are given. No significant difference between the Caucasian and Canadian East Asian group was found.

Ethnicity	Minimum Score	Maximum Score	Mean Score (±SD)
Caucasian	0	3	1.06 (1.15)
Canadian East Asian	0	3	1.57 (1.16)
East Asian, living in East Asia	4	7	4.7 (1.82)
East Asian, living in Canada	1	2	1.4 (0.54)

5.2 Hypothesis 3: Kinetics

The outcome measures (moments) were tested using a 4-way mixed model ANOVA, a summary of which can be found in Table 4.4 (2 between factors and 2 within factors; 2 levels for each factor), with all interactions. However, following the preliminary statistical testing, no interactions were found. The interaction comparisons were therefore dropped from the model in order to improve the model fit. This was done for all main outcome measures, none of which had significant interactions in the original model.

Axial rotational moments have been excluded from the results section because they do not directly pertain to the hypotheses of the study, and have not been implicated in knee OA initiation and progression.

The following tables (Table 5.3 to Table 5.6) summarize the main outcomes of this work, along with the mean and standard deviation of any significant effects. Consistently, external moments are reported with a positive flexion, positive adduction, and positive internal rotation convention.

Table 5.3

Peak knee moment summary during kneeling transitions with accompanying p-value and mean (± 1SD) values for outcomes with significant main effects.

Transition	Axis	p-value	Significant Outcomes Mean (±SD) %BW * Ht
Descent	Adduction	Ethnicity: p=0.1513	Lead 4.71 (3.04)
		Sex: p=0.1611	Trail 2.89 (2.74)
		Style: p=0.1231	
		Leg: p=0.0001*	
	Flexion	Ethnicity: p=0.0009*	Canadian East Asian 8.58 (1.82)
		Sex: p=0.4257	Caucasian 7.17 (3.08)
		Style: p=0.065	
		Leg: p=0.9024	
Ascent	Adduction	Ethnicity: p=0.1911	Lead 5.19 (3.06)
		Sex: p=0.1738	Trail 3.03 (3.29)
		Style: p=0.518	
		Leg: p<0.001*	
	Flexion	Ethnicity: p=0.0068	Canadian East Asian 8.61 (1.81)
		Sex: p=0.6436	Caucasian 7.16 (3.08)
		Style: p=0.0203*	
		Leg: p=0.5876	Plantarflexed Kneeling 8.32 (2.68)
			Dorsiflexed Kneeling 7.36 (2.45)

* indicates a significant main effect, p<0.05

Table 5.4

Peak knee moment summary during squatting transitions with accompanying p-value and mean (± 1SD) values for outcomes with significant main effects.

Transition	Axis	p-value	Significant Outcomes Mean (±SD) %BW * Ht
Descent	Adduction	Ethnicity: p=0.6001	Flat Foot 2.32 (2.11)
		Sex: p=0.6403	Heels Raised 3.76 (2.82)
		Style: p=0.0006*	
		Leg: p=0.4962	
	Flexion	Ethnicity: p=0.0035*	Canadian East Asian 6.79 (1.47)
		Sex: p=0.2737	Caucasian 5.80 (2.80)
		Style: p=<0.001*	
		Leg: p=0.2417	Flat Foot 5.28 (1.86)
			Heels Raised 7.27 (2.32)
Ascent	Adduction	Ethnicity: p=0.7627	Flat Foot 1.85 (2.27)
		Sex: p=0.1727	Heels Raised 3.19 (3.67)
		Style: p=0.0077*	
		Leg: 0.4634	
	Flexion	Ethnicity: p=0.0175	Canadian East Asian 7.13 (1.58)
		Sex: p=0.8552	Caucasian 6.26 (3.07)
		Style: <0.001*	
		Leg: p=0.4554	Flat Foot 5.55 (1.90)
			Heels Raised 7.81 (2.54)

* indicates a significant main effect, p<0.05

Table 5.5

Average knee moments and angles during static kneeling with accompanying p-value and mean (± 1SD) values for outcomes with significant main effects.

	Axis	p-value	Significant Outcomes Mean (±SD)
Moment	Adduction	Ethnicity: p=0.3622	Female 0.78 (1.10) %BW*Ht
		Sex: p=0.0433*	Male 0.41 (1.02) %BW*Ht
		Style: p=0.9714	
		Leg: p= 0.4484	
	Flexion	Ethnicity: p= 0.0436*	Canadian East Asian 7.00 (1.43) %BW*Ht
		Sex: p=0.7715	Caucasian 6.31 (2.71) %BW*Ht
		Style: p=0.0002*	
		Leg: p= 0.3912	Plantarflexed Kneeling 7.30 (2.38) %BW*Ht
			Dorsiflexed Kneeling 5.99 (1.84) %BW*Ht
Angle	Adduction	Ethnicity: p=0.055	Plantarflexed Kneeling -0.02° (4.74°)
		Sex: p=0.1788	Dorsiflexed Kneeling -1.91° (4.88°)
		Style: p=0.0134*	
		Leg: p= 0.0163*	
			Right -0.05° (5.33°)
			Left -1.89° (4.23°)

Flexion	Ethnicity: p=0.2859	Female 154.00° (5.38°)
	Sex: p=0.0075*	Male 151.26° (6.91°)
	Style: p=0.0055*	
	Leg: p= 0.1972	Plantarflexed Kneeling 153.95° (5.53°)
		Dorsiflexed Kneeling 151.17° (6.85°)

* indicates a significant main effect, p<0.05

Table 5.6

Average knee moments and angles during static squatting with accompanying p-value and mean (± 1SD) values for outcomes with significant main effects.

	Axis	p-value	Significant Angle Mean (±SD)
Moment	Adduction	Ethnicity: p= 0.5020 Sex: p=0.0587 Style: p<0.0001* Leg: p= 0.5576	Flat Foot -0.45 (1.33) %BW*Ht Heels Raised 0.59 (1.02) %BW*Ht
	Flexion	Ethnicity: p= 0.0088* Sex: p=0.8433 Style: p<0.0001* Leg: p= 0.3806	Canadian East Asian 5.54 (1.16) %BW*Ht Caucasian 4.84 (2.25) %BW*Ht Flat Foot 4.37 (1.47) %BW*Ht Heels Raised 5.99 (1.84) %BW*Ht
Angle	Adduction	Ethnicity: p= 0.3855 Sex: p=0.1167 Style: p=0.1526 Leg: p= 0.1784	
	Flexion	Ethnicity: p= 0.0014* Sex: p=0.4137 Style: p<0.0001* Leg: p= 0.4940	Canadian East Asian 147.96° (6.62°) Caucasian 141.69° (17.48°) Flat Foot 138.14° (15.82°) Heels Raised 151.17° (6.86°)

* indicates a significant main effect, p<0.05

Hypothesis 3a explores the likelihood of different styles producing significantly different moments in the sagittal and frontal planes during transitions with no ethnicity component considered. Since there were no significant interactions, the main effects of style, when applicable, were not dependent on ethnicity. A main effect for style was found during the ascent from kneeling in the sagittal plane (Table 5.3), during the ascent and descent from squatting in all planes (Table 5.4), as well as the static flexion moment for both kneeling (Table 5.5) and squatting (Table 5.6).

5.3 Electromyography

EMG was collected both to ensure that the PROM data was truly passive (<10% MVIC) and also to assess the muscle activity during static poses (Rozzi et al., 1999). Table 5.7 and Table 5.8 summarize the number of Caucasian and Canadian East Asian participants who had active muscles (>10% MVIC) during the static phase of flat foot squatting, heels raised squatting, plantarflexed kneeling and dorsiflexed kneeling. The activation between left and right legs is not significantly different during the static phase, and so data from the right leg only is shown. Data is reported as a percentage of people within the specific group whose mean EMG during static poses was >10% MVIC. The actual activation level between participants varied greatly.

Table 5.7

Percentage of total group (Caucasian (n=20); Canadian East Asian (CEA) (n=18)) who had active muscles (>10% MVIC) during the static phase of squatting (right leg).

Muscle	Flat Foot Squat		Heels Raised Squat	
	Caucasian	CEA	Caucasian	CEA
Gluteus Medius	15.0%	5.5%	10.0	0
Rectus Femoris	70.0%	50.0%	10.0%	5.5%
Biceps Femoris	5.0%	0	10.0%	0
Tibialis Anterior	100.0%	100.0%	10.0%	16.6%
Lateral Gastrocnemius	10.0%	0	15.0%	0

Table 5.8

Percentage of total group (Caucasian (n=20); Canadian East Asian (CEA) (n=18)) who had active muscles (>10% MVIC) during the static phase of kneeling (right leg).

Muscle	Dorsiflexed Kneeling		Plantarflexed Kneeling	
	Caucasian	CEA	Caucasian	CEA
Gluteus Medius	10.0%	0	10.0%	0
Rectus Femoris	10.0%	0	10.0%	5.5%
Biceps Femoris	0	0	10.0%	5.5%
Tibialis Anterior	95.0%	72.2%	15.0%	5.5%
Lateral Gastrocnemius	5.0%	0	5.0%	0

Table 5.9

Range of muscle activation during squatting (%MVC) for Caucasian (n=20) and Canadian East Asian (CEA)(n=18) participants for the right leg only.

Muscle	Flat Foot Squat (%MVIC)		Heels Raised Squat (%MVIC)	
	Caucasian	CEA	Caucasian	CEA
Gluteus Medius	1.1-11.0	0.9-10.6	1.0-10.9	0.9-9.6
Rectus Femoris	4.0-56.3	1.3-50.9	0.7-18.8	1.1-12.2
Biceps Femoris	1.2-10.7	0.7-7.8	1.0-8.9	0.2-9.2
Tibialis Anterior	14.2-91.7	12.7-60.9	1.7-14.2	0.8-17.8
Lateral Gastrocnemius	0.9-12.2	0.9-7.8	0.8-16.0	0.7-9.2

Table 5.10

Range of muscle activation during kneeling (%MVC) for Caucasian (n=20) and Canadian East Asian (CEA)(n=18) participants for the right leg only.

Muscle	Dorsiflexed Kneeling (%MVIC)		Plantarflexed Kneeling (%MVIC)	
	Caucasian	CEA	Caucasian	CEA
Gluteus Medius	1.0-10.9	0.8-10.0	1.0-11.0	0.8-9.7
Rectus Femoris	0.7-11.0	0.7-5.2	0.7-11.1	0.7-12.2
Biceps Femoris	1.6-8.9	0.7-9.5	0.9-10.2	0.7-11.2
Tibialis Anterior	9.3-42.5	4.25-27.1	0.8-19.8	1.2-12.9
Lateral Gastrocnemius	0.8-12.5	0.7-7.3	0.7-12.1	0.7-6.7

5.4 Kinetic Comparisons between Styles

An objective of this research was to establish characteristic knee moment curves for different styles of kneeling and squatting during transitions. The following figures show the external knee joint moments during all four styles of high flexion postures (Figure 5.2, Figure 5.3, and Figure 5.4), as well as the kinematics of the ankle, knee, and hip (Figure 5.1) during squatting to assist in phase visualization. Kinematics of the ankle, knee, and hip for kneeling can be found in Appendix B (Figure B.2 and Figure B.3) since there was no significant difference between mean knee flexion angle during kneeling. Moments are reported with a positive flexion, adduction, and internal rotation convention.

With respect to flexion moment, flat foot squatting results in an overall lower moment of force while the knee is full flexed (Figure 5.1). Additionally, with respect to the adduction moment, once the knee had reached the full flexion angle, the flat foot squat results in an abduction moment whereas the heels raised squat results in an adduction moment. Finally, during squatting the flat foot squat had very little variation for the mean rotational moments compared to the heels raised squatting. However, the standard deviation of both groups was quite large (one standard deviation is shown), and the overall magnitude of the rotational moment is not large (no more than ~ -0.4 %BW*Ht to 0.4 %BW*Ht).

During kneeling, the lead and trail legs were shown separately (Figure 5.3 shows the lead leg knee joint moments; Figure 5.4 shows the trail leg knee joint moments). The knee moment curves between each style of kneeling did not differ a great deal, especially in the lead leg. The trail leg knee moments showed some differences, notably in the flexion moment where the plantarflexed style of kneeling had a greater absolute range during the descending transition between ~40% and 100% Phase. The plantarflexed style of kneeling also resulted in a greater mean peak at approximately 40% Phase (both ascending and descending) compared to the dorsiflexed kneeling style in the rotational moment.

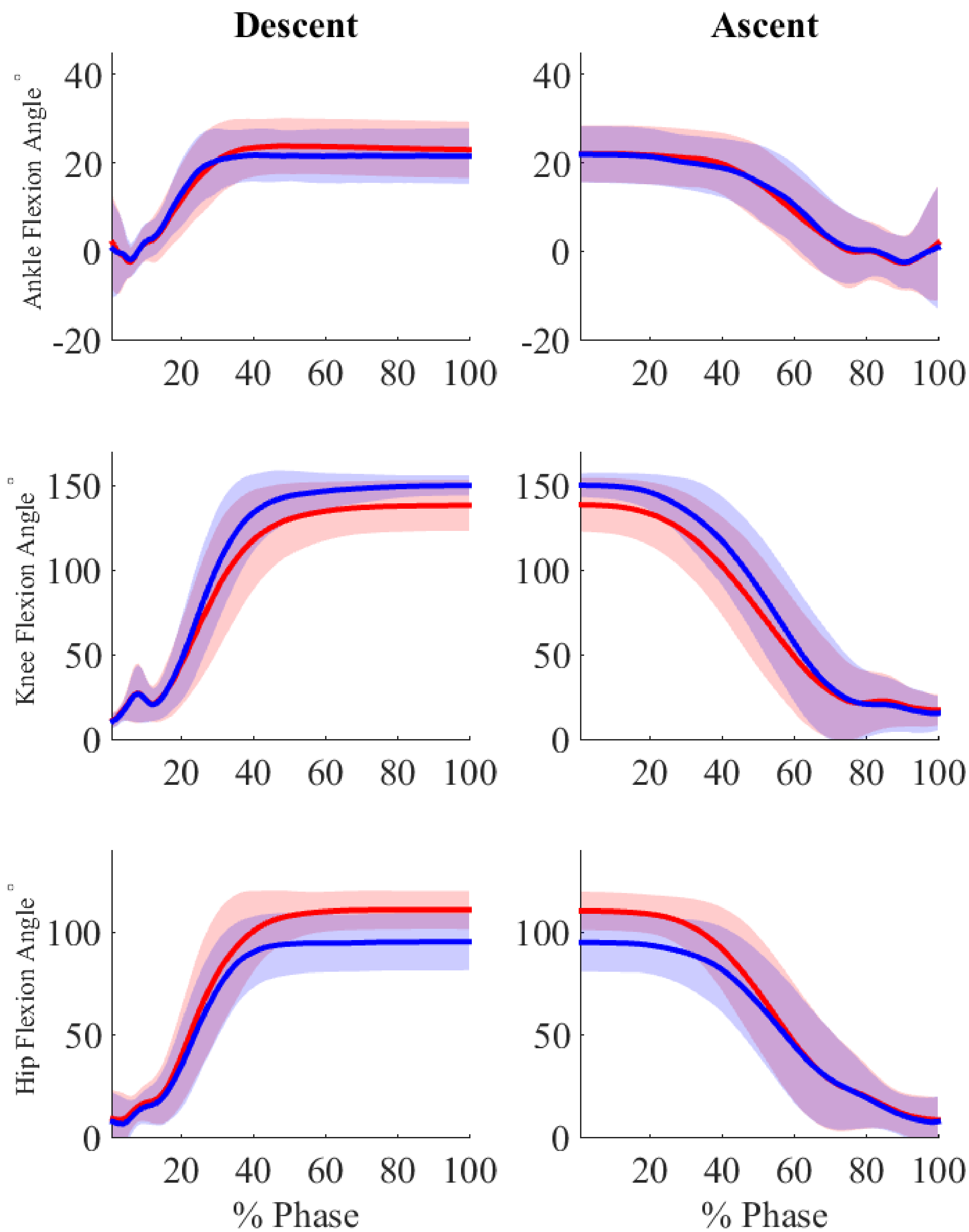


Figure 5.3 Ankle, knee, and hip flexion angles during both styles of squatting. Flat foot squatting is represented in red, and heels raised squatting is represented in blue; n=43 for both styles of squatting. The bold line represents the group mean, and the shaded areas represent ±1 SD.

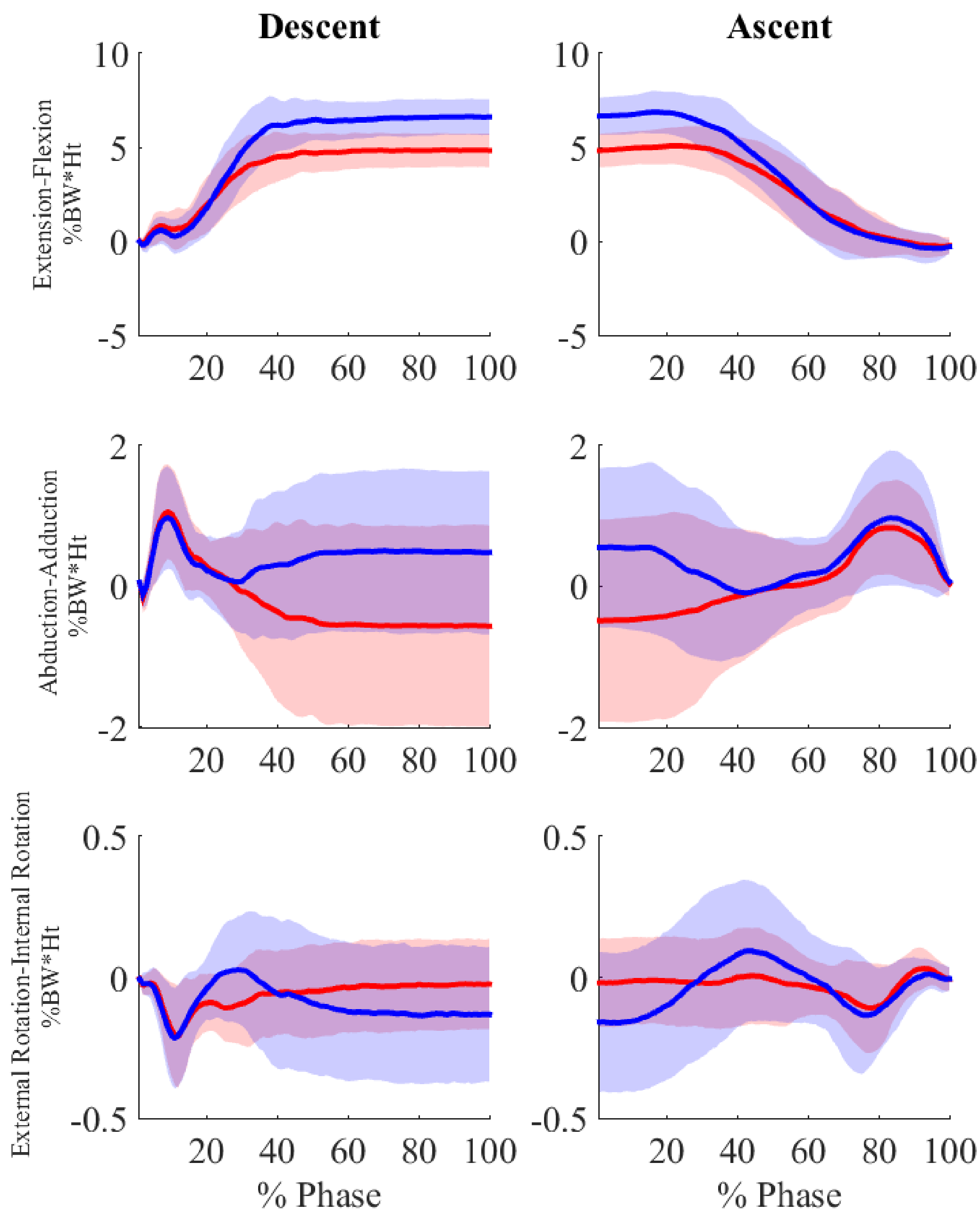


Figure 5.4 Knee flexion, adduction, and internal rotational moments during the descent and ascent of both styles of squatting. Moments are normalized to %BW*Ht. Flat foot squatting is represented in red, and heels raised squatting is represented in blue; n=43 for both styles. The bold line represents the group mean, and the shaded areas represent ±1 SD.

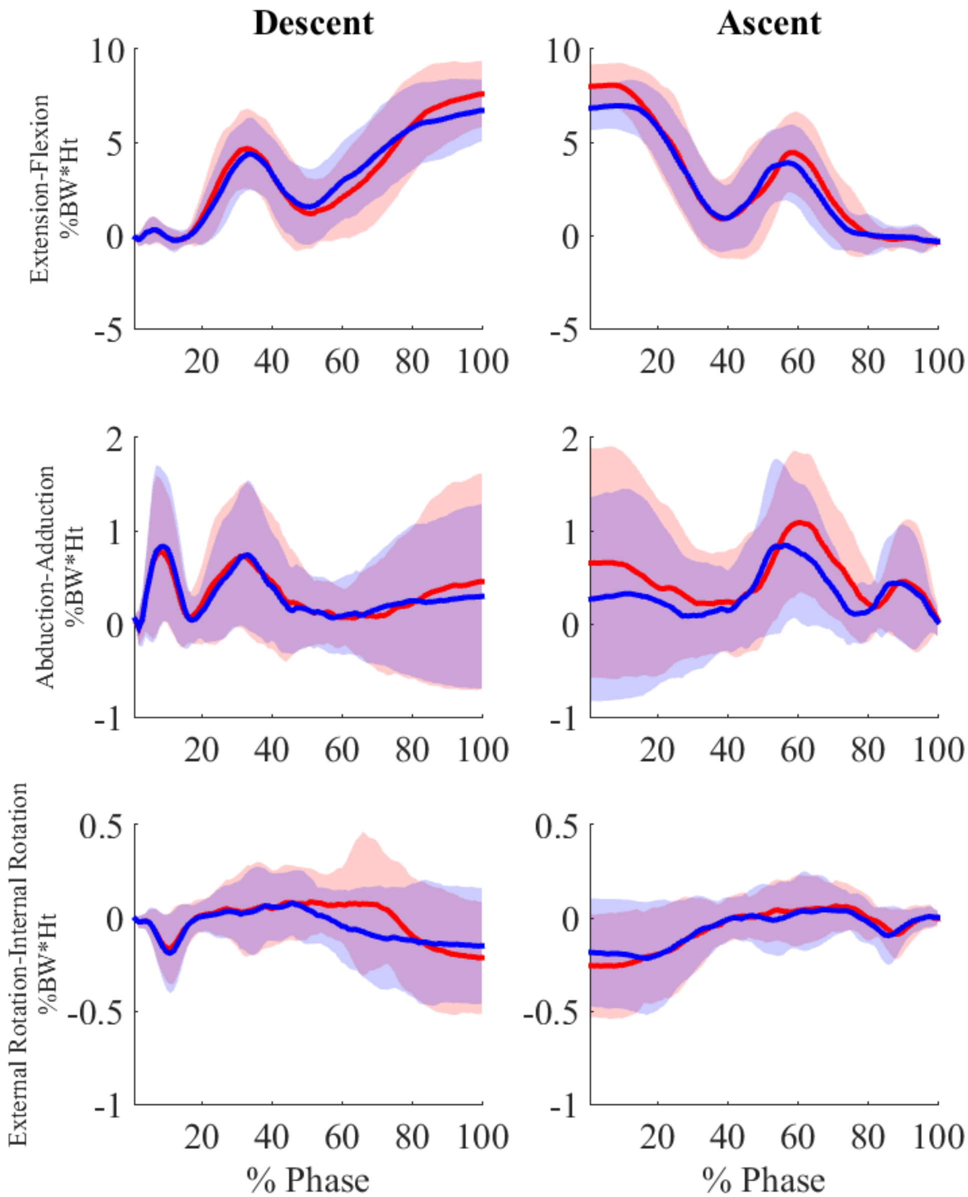


Figure 5.5 Lead leg knee flexion, adduction, and internal rotational moments during the descent and ascent of both styles of kneeling. Moments are normalized to %BW*Ht, and time normalized to 100% phase. Plantarflexed kneeling is represented in red, and dorsiflexed kneeling is represented in blue; n=43 for both styles. The bold line represents the group mean, and the shaded areas represent ±1 SD.

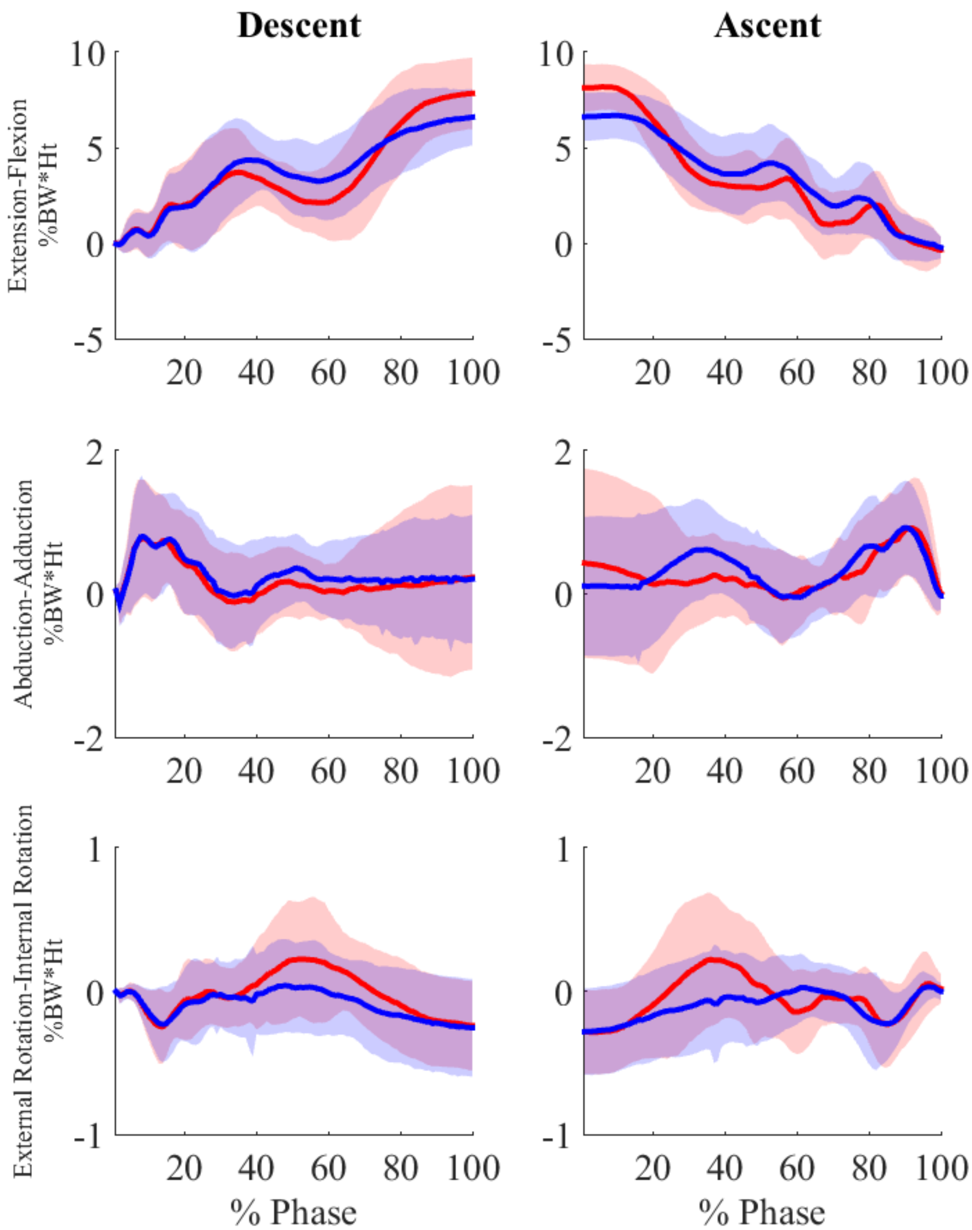


Figure 5.6 Trail leg knee flexion, adduction, and internal rotational moments during the descent and ascent of both styles of kneeling. Moments are normalized to %BW*Ht. Plantarflexed kneeling is represented in red, and dorsiflexed kneeling is represented in blue; n=43 for both styles. The bold line represents the group mean, and the shaded areas represent ±1 SD.

5.5 Results Summary

Table 5.11

Hypothesis summary, supporting evidence, and overall conclusions. The Canadian born East Asian group has been abbreviated to CEA.

Hypothesis	**Supporting Evidence** **Mean (±1SD)**	**Conclusion**
1a) East Asians will achieve a greater knee flexion angle during kneeling and squatting, regardless of foot position.	**Mean static flexion angle** **Squatting: p=0.0014** CEA 147.96° (6.62°) Caucasian 141.69° (17.48°)	Squatting: Accepted
	Mean static flexion angle **Kneeling: p=0.2859** CEA 152.00° (4.85°) Caucasian 153.10° (7.46°)	Kneeling: Rejected
1b) The difference, if found, will be a result of an	**High Flexion Frequency Questionnaire**	Squatting: Accepted

innate ability	CEA score 1.57 (1.16) Caucasian score 1.06 (1.15) (see also supporting evidence for Hypothesis 1a)	
2) East Asians will exhibit greater flexion PROM than Caucasians in the ankle, knee, and hip	**PROM Ankle Dorsiflexion: p<0.0001** CEA 21.60° (5.35°) Caucasian 13.90° (5.91°)	Dorsiflexion: Accepted
	PROM Ankle Plantarflexion: p=0.5361 CEA -29.31° (7.88°) Caucasian -28.30° (7.49°)	Plantarflexion: Rejected
	PROM Knee Flexion: p=0.1792 CEA 152.10° (8.16°) Caucasian 149.54° (7.76°)	Knee Flexion: Rejected
	PROM Hip Flexion: p=0.0069 CEA 129.90° (7.30°) Caucasian 124.97° (9.22°)	Hip Flexion: Accepted
3a) Plantarflexed kneeling and flat foot squatting will have lower moments of force at the knee in the sagittal	**Mean static flexion moment** **Squatting: p<0.0001**	Squatting: Accepted

plane (flexion moment) than dorsiflexed kneeling and heels raised squatting, respectively during static holds.	Flat Foot 4.37 (1.47) %BW*Ht Heels Raised 5.99 (1.84) %BW*Ht	
	Mean static flexion moment **Kneeling: p=0.0002** Plantarflexed 7.30 (2.38) %BW *Ht Dorsiflexed 5.99 (1.84) %BW * Ht	Kneeling: Rejected
3b) Plantarflexed kneeling and flat foot squatting will have a higher peak moment of force in the frontal plane (adduction moment) than dorsiflexed kneeling and heels raised squatting, respectively, during downwards and upwards transitions.	**Peak adduction moment** **Squatting Descent: p=0.0006** Flat Foot 2.32 (2.11) %BW*Ht Heels Raised 3.76 (2.82) %BW*Ht	Squatting Descent: Rejected
	Peak adduction moment **Squatting Ascent: p=0.0077** Flat Foot 1.85 (2.27) %BW*Ht Heels Raised 3.19 (3.67) %BW*Ht	Squatting Ascent: Rejected
	Peak adduction moment **Kneeling Descent: p=0.1231** Plantarflexed 4.23 (3.23) %BW*Ht	Kneeling Descent: Rejected

	Dorsiflexed 3.59 (2.82) %BW*Ht	
	Peak adduction moment **Kneeling Ascent: p=0.5180** Plantarflexed 4.23 (3.22) %BW*Ht Dorsiflexed 3.59 (2.82) %BW*Ht	Kneeling Ascent: Rejected

6. Discussion

6.1 Differences based on ethnicity: Hypotheses 1 and 2

6.1.1 Kinematics

A goal of this research was to assess the differences between Canadian East Asian and Caucasian ethnicities during high flexion postures. Hypothesis 1 (Canadian East Asians will achieve a greater mean knee flexion angle during kneeling and squatting, regardless of foot position) was partially confirmed, as it was found that East Asians achieved a significantly greater knee flexion angle during squatting (Figure 5.6), but not during kneeling (Figure 5.5). The difference in ethnicity during squatting seems to be largely driven by the flat foot squat; the Caucasian group had significantly less knee flexion during the flat foot squat (Caucasian mean = 131.9° (±18.8°)) than during the heels raised squat (Caucasian mean = 151.47° (±6.85°)), but during the heels raised squat, Caucasians had a more comparable mean knee flexion range to the Canadian East Asian group (CEA heels raised squat mean = 150.8° (±8.24°)). Additionally, there was no significant difference between the knee flexion PROM for each group, collected as a measure of maximal knee flexion possible (Caucasian peak PROM knee flexion angle = 149.50° (±7.76°); Canadian East Asian peak PROM knee flexion angle = 152.10° (±8.16°), p=0.17,Table 5.1). These findings indicate a difference in technique, either due to practice or limited ankle/hip flexibility, and not physical ability to achieve higher knee flexion.

A limited knee ROM does not seem to be an explanatory factor to answer why Caucasians tend to achieve a smaller knee joint angle during static squatting compared to Canadian East Asians, and so ankle ROM was explored to see if it may be a contributing factor. It was found that Caucasians and Canadian East Asians had a significantly different passive maximal dorsiflexion angle (Caucasian mean = 13.90° (±5.9°); Canadian East Asian mean = 21.60° (±5.3°), $p<0.0001$, Table 5.1). However, during the flat foot squat, Caucasians, on average, achieved a dorsiflexion angle of 22.30° (±5.9°) and Canadian East Asians had a mean dorsiflexion angle of 24.70° (±6.7°), which indicates that the active range of motion was greater than the PROM (likely as a result of full weight bearing), but also that both groups were likely very close to their end range of motion at the ankle. Based on these similarities, although the PROM is significantly different between the two groups, it seems unlikely that the flat foot squat pose is limited by the ankle joint.

Similarly to the ankle, the maximal passive hip flexion angle was significantly different between Caucasians (mean=124.90° (±9.23°)) and Canadian East Asians (mean=129.90° (±7.30°)) ($p=0.0069$, Table 5.1), but maximum hip flexion angle was not significantly different during the flat foot squat (Caucasians maximal hip flexion angle =111.80° (±8.81°) and Canadian East Asians maximal hip flexion angle = 110.20° (±5.7°); $p=0.3171$, Table 5.6). Unlike the ankle, the flat foot squat hip flexion range of motion did not reach the end of the PROM. Therefore, it does not appear that full range of hip motion is required for flat foot squatting and is not a contributing factor for why East Asians use a greater knee flexion angle than Caucasians during flat foot squatting. In addition to a main effect for ethnicity, there was a significant interaction between sex and ethnicity for the maximal PROM hip flexion angle which indicates that the relationship between males' and females' maximal passive hip flexion angles is different depending on ethnicity. In this case, males had a lower flexion angle in comparison to females for the Caucasian participants, but had a higher flexion angle than females within the Canadian East Asian participants. The hip PROM values for both ethnicities and sexes were within reported ranges of approximately 120° in healthy participants (Arokoski, Haara, Helminen, & Arokoski, 2004).

Although the frequency of high flexion questionnaire showed no differences in outcome score between Caucasian and Canadian East Asian participants, it is possible that the Canadian East Asian participants are able to achieve a greater knee flexion angle during squatting because they are culturally more exposed to the postures; although they may not practice them on a regular basis, they may have seen their parents squatting and be more familiar with the task in terms of balance requirements. Hypothesis 1b (differences in high flexion ability will be a result of innate ability, as opposed to practice) is nullified since there is no difference between ethnicities with respect to knee flexion ability from the PROM.

6.1.2 Kinetics

Although this study did not aim to find and did not expect any differences based on ethnicity with respect to different moments of force exerted on the knees during kneeling or squatting, it was found that during transitions and during static holds, Canadian East Asians experience a significantly higher flexion moment in the knees than Caucasians (Table 5.3 to Table 5.6). Throughout the ascent, descent, and static holds for both kneeling and squatting, Canadian East Asians experience a significantly higher knee flexion moment, with differences between ethnicities varying between 0.69 %BW*Ht (during static kneeling) and 1.58 %BW*Ht (during the ascending squat transition). The kinetic curves showing the ascending and descending transitions as a comparison between ethnicities for all four high flexion postures can be found in Appendix B.

During squatting transitions several possibilities were explored to characterize this difference, the most viable of which is that there was a difference between the ankle flexion angle at the time of peak knee flexion moment between ethnicities. At the point of peak knee flexion moment during squatting descent (which coincides with the static hold, Figure 5.2), Canadian East Asians experienced on average 26.5° (±4.32°) dorsiflexion at the ankle, compared to Caucasian participants who experienced on average 22.9° (±6.52°) dorsiflexion ($p=0.043$). By increasing the dorsiflexion angle at the ankle, the tibia angles more horizontally relative to the ground (since the participant's foot must be entirely on the floor, forefoot flexion is not a factor). This would act to increase the moment arm length from the point of the center of mass (where the segment mass and gravity are applied) to the proximal end of the tibia where the knee joint moment is applied. The corresponding ascending transition was not significantly different between ethnicities with respect to ankle angles (Canadian East Asians experience 23.4° (±4.41°) and Caucasians experience 20.6° (±5.74°)). However, there was still a statistically significant difference in peak flexion moment (Canadian East Asian mean peak flexion moment = 7.13 (±1.58) %BW*Ht and Caucasian mean peak flexion moment = 6.26 (±3.07) %BW*Ht, Table 5.4). The difference in dorsiflexion angles, although non-significant, was 2.8°, only slightly less than the difference during the descending transition (which was significant), and may still have contributed to the ethnic difference between peak flexion moments.

The static squatting pose had a significant difference between ethnicities for both the knee flexion moment and the knee flexion angle. Thus, the knee flexion angle, which is greater in Canadian East Asians than Caucasians, would have changed the center of pressure location of the foot, reflective of the position of the center of mass of the body, which altered where the ground reaction force was applied (Figure 6.1). Effectively, the change in center of pressure location results in an increased moment arm along the long axis of the foot, increasing the moment at the ankle, which in turn, would increase the moment at the knee assuming the other factors are equal. Although the average static ankle moment was not significantly different between ethnicities, it may have been a contributing factor to the overall difference between ethnicities seen at the level of the knee. Figure 6.1 shows how the changing COP location as a result of change in knee angle may have affected the ankle flexion moment. During flat foot squatting Canadian East Asians had a greater knee angle and a greater ankle dorsiflexion angle, which results in a shorter moment arm length from the GRF (applied at the COP) to the ankle joint (shown in Figure 6.1) as well as a greater contribution from the force due to gravity acting at the center of mass of the shank . Both of these factors contributed to the significant difference in peak knee flexion moment seen in Canadian East Asians compared to Caucasian participants.

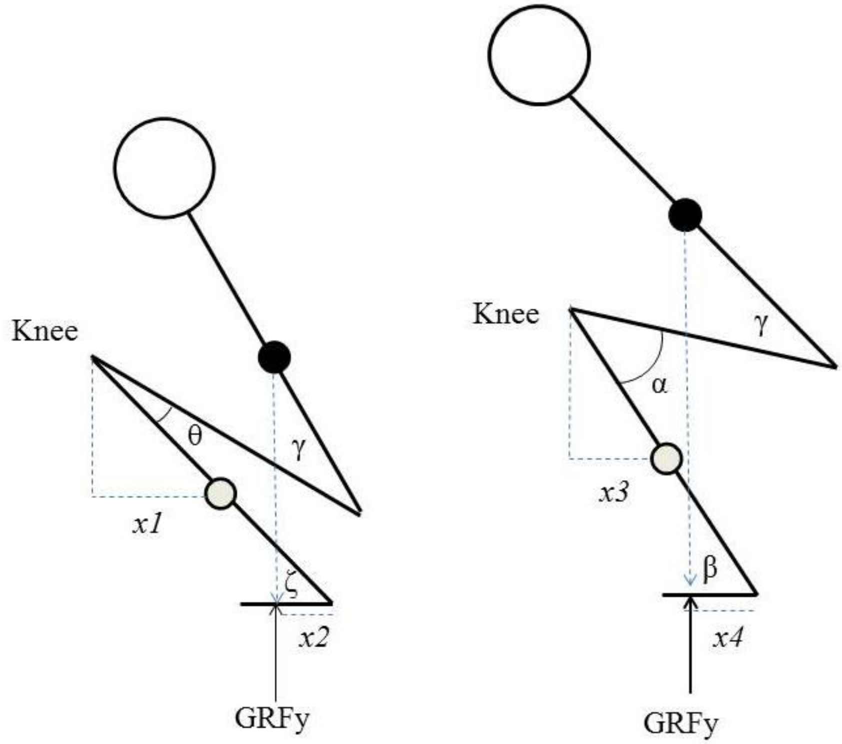


Figure 6.1 Flat foot squat with different knee angles (θ and α) and ankle angles (ζ and β). The hip angle (γ) is consistent between poses. The increased knee angle α (lower flexion angle) causes the COP in the foot to translate anteriorly, which increases the moment arm length from the application of the GRFy to the ankle joint center (*x4* is longer than *x2*). The increased ankle angle ζ causes the moment arm length (*x1*) from the center of mass of the shank (grey circle) to the knee joint center to be greater than the moment arm length (*x3*) when the dorsiflexion angle is decreased (ankle angles were normalized to a standing reference posture; therefore, a more acute angle is a greater dorsiflexion angle).

Canadian East Asians had a higher peak knee flexion moment at the knee during kneeling transitions and static kneeling by approximately 15% during transitions and 10% during static kneeling (Table 5.3 and Table 5.5). The difference in flexion moment at the knee was caused in part by a difference in the phase at which the peak flexion moment occurred for each ethnicity.

In Canadian East Asians, the peak flexion moment occurred most frequently during a deep lunge position, immediately before the trail knee made contact with the ground (mean lead knee flexion angle at time of peak flexion moment=139.3° (±16.5°); mean trail knee flexion angle at time of peak flexion moment=143.5° (±19.3°)). However, in Caucasians the peak flexion moment occurred once the participant is nearly in full flexion, and the mean knee flexion angle at the time of peak flexion moment for both legs was 148° (±9.01°). The large standard deviation seen in the Canadian East Asian group indicates that not every participant reached the peak flexion angle during the transition, which was associated with a higher flexion moment than static kneeling. However, the higher flexion moment seen during transitions outweighs the lower flexion moment that occurs later in the pose (closer to full flexion), to the extent that the difference was great enough to reach statistical significance. Since seven out of 18 Canadian East Asian participants reached their peak knee flexion moment during full flexion kneeling (instead of during the transition), caution should be used when comparing ethnicities to ensure that the difference in peak flexion moment during kneeling is not simply caused by a difference in timing with respect to when the peak flexion moment occurs which may, or may not, always be related to ethnicity. Based on the high variability between participants, the exact mechanism of increasing the peak flexion moment during transitions for Canadian East Asians is unknown but is likely a combination of differences in technique and temporal occurrence of peak flexion moment.

6.1.3 Cultural Use of High Flexion Postures

It has been well reported that East Asians use high flexion postures for a wider range of ADLs than typical Caucasian adults living in North America (Akagi, 2005; Mulholland & Wyss, 2001; Takano et al., 2008). There are many potential reasons for this difference in life style, amongst them poverty, religious practices, and ability (Takano et al., 2008). However, it is extremely difficult to quantify these reasons. Based on the EMG data collected during the static poses for both kneeling and squatting, it is possible that a contributing factor to the increased use of high flexion in East Asian cultures is the amount of physical effort holding the pose requires. In all of the kneeling and squatting styles (with the exception of tibialis anterior, which was required by the majority of participants in both groups), the Canadian East Asian group had fewer people who required muscular activation during the static holds for both styles of kneeling and squatting (Table 5.7 and Table 5.8). Being able to keep certain muscles passive during prolonged static holds would likely increase the length of time that the pose would be practical to hold by reducing muscular effort. During flat foot squatting and dorsiflexed kneeling, both groups had a very high percentage of people who required an active tibialis anterior (72%-100% of people), but with the exception of tibialis anterior, only one pose and one muscle group (flat foot squatting, rectus femoris) required greater than 10% of people to have active muscles for the Canadian East Asian group. It is hypothesized that since the increased knee flexion angle seen in Canadian East Asians during squatting is closer to the participant's end range of motion, it would enable the participant's to have a more passive posture which may increase comfort and sustainability. In comparison, the majority of poses required at least 15% of Caucasians to have the majority of their muscles active. This finding does not indicate that every Caucasian participant was unable to use high flexion in a passive manner, but that a greater percentage of the Caucasian group were unable to be passive in the high flexion postures, indicating greater physical requirements. Since both groups were infrequent users of high flexion, it's possible that a more practiced group would be able to further reduce muscular contribution during high flexion and increase the sustainability of high flexion postures.

In particular, greater muscular activation may be used as a balance strategy to correct for deviations from the base of support. During the flat foot squat, Caucasian participants had greater muscular activity which may have been correcting for balance (one Caucasian participant fell over backwards; this trial was discarded, but balance was clearly an issue for this participant), although research on experienced Indonesian squatters indicates that the flat foot squat is a more stable pose (Sriwarno, Shimomura, Iwanaga, & Katsuura, 2008). The static hold for each pose was eight seconds long, which is not comparable to using a specific posture for most ADLs. Therefore, although this short time showed a greater number of Canadian East Asians who had passive leg muscles, a much longer length of static trial should be collected to establish the muscle activation patterns in a more realistic time frame.

6.2 Differences in kneeling and squatting styles: Hypothesis 3

Hypothesis 3a examines differences in the average knee moments during static poses, while 3b focuses on the differences in peak knee moments during transitions between the two styles of kneeling and squatting.

6.2.1 Static Kneeling and Squatting

Hypothesis 3a examined potential differences between styles of kneeling and squatting regardless of ethnicity contributions. The intent of comparing two different kneeling and two different squatting styles is to form recommendations on reducing the moment at the knee joint while using these poses since it has been implied that an increased knee joint moment (in particular, the peak knee adduction moment) may increase the likelihood for knee OA initiation and disease progression (Baliunas et al., 2002). Hypothesis 3a is as follows:

Plantarflexed kneeling and flat foot squatting will have lower moments of force at the knee in the sagittal plane (flexion moment) than dorsiflexed kneeling and heels raised squatting, respectively, during static kneeling.

During static kneeling, it was found that plantarflexed kneeling had a significantly higher flexion moment than dorsiflexed kneeling (plantarflexed kneeling 7.30 ± (2.38) %BW*Ht; dorsiflexed kneeling 5.99 ± (1.84) %BW*Ht, Table 5.5). The most likely reason for the increase in flexion moment is that participants had a greater mean knee flexion angle during plantarflexed kneeling (153.95° ± (5.53°)) than during dorsiflexed kneeling (151.17° ± (6.85°), Table 5.5). During kneeling, the ground reaction force is applied at the foot as well as at the tibial tuberosity (the ground reaction forces are from two separate force plates). In the rigid link segment model, the foot-ground reaction force contributes to the ankle moment. Both the resulting ankle moment and the knee-ground reaction force then contribute to the knee moment. By increasing the flexion angle at the knee during plantarflexed kneeling, the participants have a greater proportion of their body mass distributed towards their feet instead of their knees. The relative increase in mass on the feet during plantarflexed kneeling increases the moment contributed from the ankle (since the initial ground reaction force at the foot would be greater with more mass applied) and decreases the contribution from the vertical ground reaction force applied at the knee (since the knee-ground reaction force is lower). The relatively higher moment at the ankle during plantarflexed style kneeling would then drive the overall increase in flexion moment seen at the knee. Based on these findings, with respect to kneeling, we reject hypothesis 3a for kneeling and conclude that Asian style kneeling (plantarflexed kneeling) has a higher flexion moment (contrary to the hypothesis).

Although hypothesis 3a was rejected for kneeling, hypothesis 3a was accepted for squatting. It was found that Asian style squatting (flat foot squatting; 4.37 ± (1.47) %BW*Ht) had a lower flexion moment at the knee compared with heels raised squatting (5.99 ± (1.84) %BW*Ht, Table 5.6). The flat foot squat has a lower flexion moment than the heels raised squat, likely as a result of where on the foot the ground reaction force is applied (Figure 6.2). During heels raised squatting, the force is applied at approximately the head of the metatarsals at the COP of the foot, which results in a longer moment arm for the moment at the ankle (moment arm length will be from the ankle joint center to the metatarsals; essentially, the length of the foot) which increases the moment at the ankle and then knee. In contrast, the flat foot squat requires the heels to be on the ground which causes the COP to translate posteriorly along the midline of the foot, shortening the moment arm of the ground reaction force in the ankle moment calculation. This decrease in moment at the ankle directly influences the knee moment as it moves up the kinetic chain to the knee.

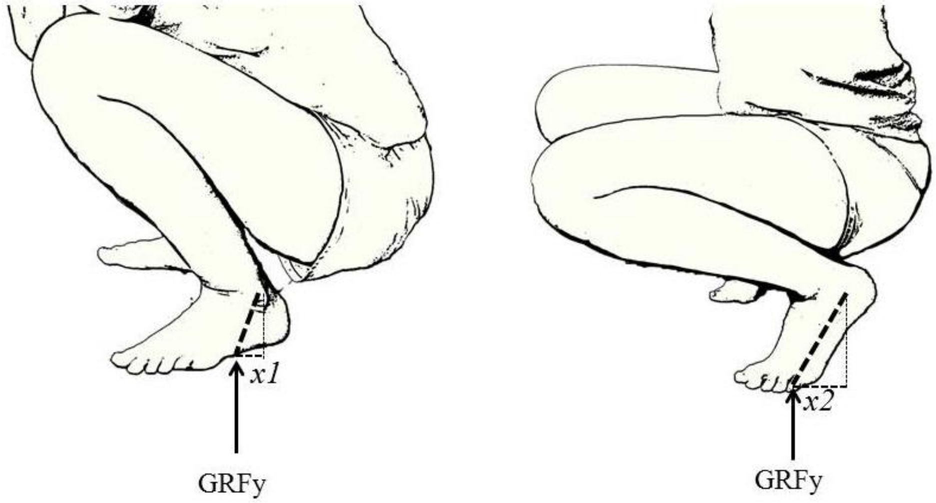


Figure 6.2 The vertical ground reaction force (GRFy) during heels raised squatting is applied at the heads of the metatarsals, which increases the moment arm length (*x2*) compared to flat foot squatting where the GRFy is applied at the mid-foot (the moment arm of the GRFy and the ankle joint is shorter (*x1*)).

Both kneeling and squatting resulted in a peak flexion moment that is considerably higher than is seen during non-pathological gait, which is typically ~3% BW*Ht (Moisio, Sumner, Schott, & Hurwitz, 2003). However, the values seen during kneeling and squatting in a static pose may be falsely inflated since thigh calf contact is neglected in this model. Based on work by Zelle et al. (2009), ignoring the effects of thigh calf contact may result in an inflated knee flexion force by approximately 60% (the authors found a decrease in compressive knee force from 4.89 to 2.90 times bodyweight during maximal high flexion squatting when accounting for thigh calf contact). This work by Zelle et al. (2009) was quite limited with respect to how many participants and scenarios the thigh-calf contact equation was applied to (the thigh calf contact model was applied to only a single participant from a previously collected study). Since only a change in joint contact force (and not net joint moment) was reported, it is impossible to determine the corresponding change in net joint moment, but it is reasonable to expect that including thigh calf contact would reduce the flexion moment at the knee.

Knee OA is more strongly associated with medial knee loading (Lewek et al., 2004), which can be represented by knee adduction moments during activities. During static kneeling and squatting, which may be a prolonged exposure depending on why the posture is being used (for example, Chinese women were only classified as frequent squatters if they squatted for longer than 6 hours daily (Das et al., 1994)), a higher knee adduction moment may be especially problematic. During static squatting, flat foot squatting resulted in an abduction (-0.45 ± (1.33) %BW*Ht) moment as opposed to an adduction moment seen during heels raised squatting (0.59 ± (1.02) %BW*Ht), indicating that heels raised squatting would tend to load the medial compartment more than flat foot squatting. The change in moment direction is likely a direct result of foot positioning; during flat foot squatting, the external rotation of the foot placement is driven by the hip for most participants which results in increased knee joint congruency. During heels raised squatting, the feet were externally rotated (toe-out) through rotation at the knee (as well as at the hip) which likely contributed to the difference in moment. Both toe in and toe out changes in gait have been shown to increase the external knee adduction moment (depending on the phase of gait) as a result of the COP location changing, resulting in a change in the length of the moment arm of the vertical ground reaction force with respect to the knee joint center; a similar mechanism is likely occurring in the heels raised squatting, where the foot COP is farther from the knee joint center, increasing the moment arm length and the overall external knee adduction moment (Shull et al., 2013; Simic, Wrigley, Hinman, Hunt, & Bennell, 2013). These values are quite low compared to values seen during transitions (Table 5.4 and Table 5.6), but could be exerted on the knee joint for a much longer period of time, resulting in a larger cumulative load.

During static kneeling, it was found that females have a greater mean knee flexion angle (154.00° (±5.38°)) compared to males (151.26° (±6.91°)), as well as a greater mean knee adduction moment (0.78 (±1.10) %BW*Ht) than males (0.41 (±1.02) %BW*Ht). This finding was not replicated during static squatting. Based on previously reported sex differences, the greater flexion angle in females than males was anticipated for the Caucasian group (Leszko et al., 2011), but was not expected within East Asian participants (Han, Cheng, & Xu, 2015). However, since no interaction was found, within this specific testing population ethnicity was not found to play a role in the differences of flexion angle between sexes. There is evidence that a greater knee flexion angle in Caucasian females is due to an inherently greater knee joint laxity in comparison to males (Rozzi et al., 1999). The increase in joint laxity may also alter the area of loading during kneeling between participants. Therefore, the greater joint laxity in females may have resulted in less weight distribution between the lateral and medial boarders of the knee, increasing medial knee loading (a greater mean adduction moment during static kneeling).

6.2.2 Ascending and Descending Transitions

Hypothesis 3b focuses on differences in kneeling and squatting styles during transitions, without an ethnicity consideration:

> *3b) Plantarflexed kneeling and flat foot squatting will have a higher peak moment of force in the frontal plane than dorsiflexed kneeling and heels raised squatting, respectively, during downwards and upwards transitions.*

During squatting transitions, the highest peak flexion moments occurred at the participants' end range of motion (full squatting pose) (Figure 5.2), which is essentially a static squatting pose. The slight discrepancy between values between the static mean and the transitional peak is attributed to the difference of a mean value over the entire static hold, and the single peak value at the end of transition. The squatting peak adduction moment during transitions, however, did not occur at the point of peak knee flexion angle and was more than double the moment during static holds (and was a peak adduction moment as opposed to an abduction moment during the transition into and out of flat foot squatting). The knee adduction moment was significantly higher in heels raised squatting during descent (p=0.0006, Table 5.4) as well as during ascent in comparison to flat foot squatting (p=0.0077, Table 5.4). During heels raised squatting the mean peak knee adduction moment during descent was 3.76 (±2.82) %BW*Ht, and during ascent was 3.29 (±3.67) %BW*Ht. Hypothesis 3a predicted that East Asian style squatting would have a greater peak knee adduction moment than heels raised squatting; this hypothesis can now be rejected since it was found that the opposite was true. During gait, an increased external knee adduction moment has been found in participants with moderate to advanced knee OA; the finding that participants who have very mild knee OA also exhibit an increased knee adduction moment suggests that a high knee adduction moment may be intrinsically associated with the pathogenesis of knee OA (Baliunas et al., 2002). This relationship may extend to increased peak knee adduction moments in high flexion, which would indicate that using a flat foot style of squatting may be preferable to reduce knee adduction moments during transitions and static squatting in comparison to a heels raised style.

There are several outcomes that should be noted with respect to transitional kneeling. It was found that no difference exists between styles of kneeling with respect to the peak knee adduction moment during transitions (Table 5.3), likely because the transitional phase of each style of kneeling is very similar. The difference in style was defined by the foot position during the static hold (the ankle was either plantarflexed or dorsiflexed), which resulted in the participants using very similar strategies until the end when the ankle position was altered (Appendix B, Figure B. 2 and Figure B. 3). Given the similarities found during transitions, hypothesis 3b for kneeling was rejected since no difference in style was found. However, it was found that the lead leg, which generally went through a greater weight bearing phase than the trail leg while in a highly flexed position, was associated with a higher knee adduction moment during ascent and descent than the trail leg. The lead leg peak adduction moment occurred in most people just before the trail leg made contact with the force plate (Figure 5.3 and Figure 5.4). At this instant, the participant was supporting the majority of their body weight (~60% within this population) on their lead leg, which would have contributed to the increased knee adduction moment seen at this point during transitions. An increase in lead leg peak knee adduction moment has been replicated in another study using a similar style of kneeling (Chong et al., submitted). In conjunction with the possibility that an increased knee adduction moment may increase the likelihood of knee OA progression or initiation, in instances where one knee is affected, the sound knee should be used as the lead leg in order to prevent further damage to the affected joint.

7. Limitations

In high flexion research, the soft tissue deformation experienced at the calf and thigh are a major challenge for skin-mounted marker based motion tracking. An assumption of rigid link modeling is that the each segment is a non-deformable solid; during most research (non-high flexion), this assumption is reasonable since there is not a significant amount of soft tissue deforming around the bone. However, during high flexion postures the thigh and calf deform quite extensively and this deformation cannot be prevented. In particular, the lateral aspect of the thigh (where the rigid marker cluster was placed in this study) translated laterally when the thigh was compressed which may have falsely increase the adduction angles and moments calculated. However, both kinematics and kinetics were tested using a repeated measures ANOVA for each dependent variable. By analyzing these variables as repeated measures, although the mean differences between each group may have been small -in particular, mean adduction angle during kneeling differed by approximately 2°, but was significantly different between plantarflexed kneeling (-0.02° (4.74°)) and dorsiflexed kneeling (-1.91° (4.88))- the actual differences between individuals may have varied greatly (a range of adduction angles from -14.9° to 14.5° was found). Additionally, the rigid clusters used in this experiment were made to fit an approximately a 50th percentile male leg circumference which may have not been appropriate for the range of participants (the average male Caucasian maximal thigh circumference was 54.04 (± 6.02) cm which was the largest group, compared to the average female East Asian maximal thigh circumference was 48.5 (±2.21) cm which was the smallest group, Table 4.1). The rigid cluster being too big was problematic because the edges had a tendency to get caught behind the participant's knee, resulting in a falsely inflated external rotation measure. On the shanks, an overly large cluster resulted in the cluster being moved proximally up the shank in order to avoid the cluster contacting the ground during kneeling poses (the cluster overhung the shank both anteriorly and posteriorly resulting in the cluster physically stopping at the point of ground contact, but the shank continuing to compress). Although soft tissue deformation will continue to be a limitation in the area of high flexion research, mitigation of inaccuracies could be improved by creating smaller clusters which are less prone to rotation about the participant's thigh and less likely to overhang the participant's legs.

Although the majority of kneeling and squatting high flexion papers have neglected to account for thigh-calf contact (Dahlkvist et al., 1982; Hefzy et al., 1998; Nagura et al., 2002), incorporating thigh-calf contact alters the moments of force about the knee and is a limitation of this study. Neglecting thigh-calf contact could cause models to overestimate tibiofemoral joint contact forces in high flexion positions since the incorporating thigh-calf contact allows for the contact area of force to be spread out over the entire area in contact. In an initial assessment, incorporating thigh-calf contact was found to decrease the compressive knee force in the knee by approximately 60% (Zelle et al., 2009). However, attempting to characterize thigh-calf contact is still in its infancy and so was neglected from this study as is typical in high flexion research. Furthermore, neglecting thigh-calf contact would only be a limitation beyond the contact initiation point of approximately 130˚, which implies that although the static poses may have a falsely inflated flexion moment, the peak transitional moments that did not occur at maximal flexion would be unaffected by the addition of thigh-calf contact (Zelle et al., 2007). Although the magnitude of knee moments may be inflated in postures exceeding approximately 130°, the comparison between styles should be relatively unaffected during kneeling. The amount of thigh-calf contact during high flexion is associated with the flexion angle of the posture, and since there was no significant differences found in flexion angle between kneeling styles, the amount of thigh-calf contact should be similar and affect the moment at the knee similarly. During squatting, the knee flexion angle during flat foot squatting (138.1° (15.8°)) is lower than during heels raised squatting (151.2° (6.9°)). Since flat foot squatting is associated with a lower moment of force, a lower flexion angle would imply that this value is less inflated in comparison to the heels raised squatting style. Since flat foot squatting has a lower knee flexion moment during the static phase without the addition of thigh-calf contact and a lower flexion angle at the knee, the difference between flat foot squatting and heels raised squatting would be reduced by an unknown amount, compared to what was reported in the current study, by incorporating thigh-calf contact. The slight difference in thigh and calf circumference between ethnicities (Caucasian MTC=53.4 (0.85) cm; Canadian East Asian MTC = 51.1 (0.37) cm; Caucasian MCC = 36.5 (0.43) cm; Canadian East Asian MCC = 36.0 (0.83) cm), would imply that Caucasians are slightly more affected by thigh-calf contact as a result of greater thigh and calf circumferences (likely resulting in larger thigh-calf contact areas). Therefore, the lower moments seen in Caucasians would persist with the addition of thigh-calf contact since the Caucasian values would decrease more than the Canadian East Asian knee moment values.

8. Contributions and Future Directions

This section summarizes the novel contributions from this research. At the most basic level, kinetic transitions into and out of high flexion postures have not been well reported, and the moment curves have not been published; these transitions have now been characterized in this research. Additionally, the discrepancy between flexion angles reported from Caucasian and East Asian individuals was a point of contention between different sources of literature. The current study, which used identical protocols for two different ethnicity groups, agrees with the only other previous study to do so (Leszko et al., 2011). Thus, it can now be more firmly suggested that differences between reported values between ethnicities is a result of unreported measurement techniques or protocols resulting in different outcomes, and that the ability to achieve greater knee flexion in East Asians is likely unfounded. However, although the knee flexion angle that can be achieved between ethnicities is not different, a valuable contribution is the discovery that East Asian participants encounter a higher flexion moment of force during high flexion postures (both kneeling and squatting). This finding should be used when modeling high flexion postures in different ethnicities to accurately represent knee joint loading.

With respect to differences in styles, this work has established that flat foot squatting produces lower moments of force about the knee when compared to heels raised squatting. This finding could be used when making recommendations for safer squatting practices in people with knee pain or knee joint injury who are required to use a high flexion squat (for example, squatting is becoming a more common birthing position for women who prefer an upright delivery stance (Gupta, Hofmeyr & Shehmar, 2012; Nasir, Korejo & Noorani, 2007)). Additionally, the finding that the lead leg undergoes a greater adduction moment in comparison to the trail leg could be taken into consideration when getting into or out of a kneeling posture if one leg is more susceptible to joint pain (for example, knee OA or previous joint injury in one leg only). The sound leg should be used as the lead leg, while the less healthy leg should be used as the trailing leg.

In the immediate future, completing the East Asian born in East Asia group would be beneficial to determine if any differences seen between the Canadian born East Asian group and the Caucasian group is exacerbated by the addition of a frequent high flexion cultural upbringing. A difference between East Asian born in East Asia and Canadian East Asians would indicate that not only is there an innate effect for squatting (based on the difference between Canadian East Asians and Caucasians with no difference with respect to high flexion frequency in ADLs), but that there is also a practice effect such that people who use high flexion on a regular basis may have a different kinematic or kinetic strategy. Additionally, collecting data from other age groups (age ranged from 18-35 years of age in this study) would determine age related differences of high flexion in a non-frequent kneeling population.

Another question that is directly related to this work is the effect of long term static holds. Anecdotally and based on empirical research, East Asian cultures are able to sustain high flexion postures (typically flat foot squatting in China and plantarflexed style kneeling in Japan and other East Asian cultures) for far longer than is comfortable in Caucasian individuals (Das et al., 1994 only categorized elderly Chinese participants as frequent squatters if the participant reported squatting for >6 hours daily; by contrast, Jensen et al., 2010, reported maximal time spent in knee straining postures as 2.5 hours within a Western population). It would be worthwhile to do a prolonged kneeling and squatting protocol while monitoring muscle activity to determine if different muscle activation patterns may contribute to why East Asians seem more comfortable with high flexion postures over a longer period of time.

The PROM data collected for this work lays an interesting foundation for exploring joint stiffness between ethnicities. Stiffness ($k = \Delta M/\Delta\alpha$, where M is moment, and α is rotational angle) is based on the joint angle and moment (calculated based on force transducer data and the distance the force transducer was applied from the joint center; a consistent distance would result in a consistent moment arm length). To ensure quality data, along with the PROM protocol used in this study, two main additions should be made. First, a consistent starting angle (especially in the ankle where greater variability was found within the PROM) is necessary to prevent non-comparable data ranges; within the PROM data set, some participants had a greater plantarflexion starting angle than other participant's end range. This would present a problem for analysis of stiffness at specific angles, since even at the initial ranges not every participant would have a value. The solution to this problem would be to have all participants start at a specific angle for every trial. The second modification for the addition of a stiffness coefficient is with respect to the participant's posture during the PROM knee trials. In the current PROM description the participants lay prone, and their knee was flexed from a neutral posture (approximately 0-5° flexion depending on the participant) to as far as the participant could be moved (heel gluteus contact was common). However, as the participant moved through 90° flexion and further, gravity acted on the tibia allowing the shank to fall towards the buttocks without experimenter intervention. The result of this is that during mid-range flexion with the use of a force transducer, the data would appear as though no force is required, when, of course, the force required is based on gravity. In the current set up (with the participant prone), gravity would work against the force transducer up until the shank was vertical, and then would work with the force transducer once the shank was past vertical (greater than 90° flexion). Therefore, the modification to accommodate a knee joint stiffness calculation would be to have participants lay on their side with the leg propped at a horizontal angle from the hip during this test, so that the action of gravity is consistent throughout the range of motion instead of acting on either side of the joint rotation.

In the future, greater standardization of reporting techniques would be beneficial to this field. Comparative data is scarce, and data that is available frequently neglects to report the joint coordinate systems, coordinate system in which the moment is resolved, or normalization techniques (further, the anthropometric data is often unavailable, making comparisons between different normalization techniques difficult or impossible).

Finally, a long term future direction is the testing and implementation of ethnicity specific TKAs. Currently, East Asian populations have a higher rate of TKA refusal compared to Western populations, likely as a result of a fear of inability to maintain a life style that requires high flexion postures (Akagi, 2005). Although there is some evidence that newer TKAs are able to meet the required flexion ranges (Acker et al., 2011), there is also evidence that the TKA does not allow for required ADLs or that the implantation into East Asian recipients is less successful (generally as a result of component oversizing) (Hemmerich et al., 2006; Iorio et al., 2007; Vaidya et al., 2000). This project could be used as a platform for improving TKA design testing protocols since the required angles and moments are clearly outlined for high flexion styles that are typically used by East Asian participants. In addition to the contributions of this study, knee joint modeling would be required to determine joint contact forces, a more exact method of motion tracking would be required to determine joint translations, and, ideally, thigh-calf contact contributions would be included.

9. Conclusion

The primary purpose of this research was threefold: first, to examine the difference in flexion angle that can be achieved by Canadian East Asians and Caucasians; second, to determine if the difference, if present, is innate or a result of cultural upbringing; and third, to determine if differences in kinetics exist between different styles of high flexion postures. Although kinematic analyses of high flexion have been reported, a discrepancy between the ability of different ethnic groups had not been substantiated (Akagi, 2005; Hefzy, Kelly, & Cooke, 1998; Hemmerich et al., 2006; Leszko et al., 2011). Further, kinetic analysis of high flexion, particularly bilateral analysis during transitions entirely to full flexion, had not been reported (Nagura et al., 2006; Pollard et al., 2011), and a kinetic comparison of ethnicities is completely novel.

Canadian East Asians and Caucasians have different high flexion requirements. Canadian East Asians typically use high flexion as a form of ADL, whereas Caucasian North Americans use high flexion with far less frequency, unless required for occupational, religious, or leisure practices. However, there does not appear to be a difference in ability with respect to the flexion angle obtainable by each ethnicity since, in kneeling and during PROM testing, the same flexion angle was reached. Based on this finding, it was concluded that Canadian East Asians and Caucasians can achieve the same knee flexion angle and so there appears to be no innate difference based on ethnicity. However, the Canadian East Asians and Caucasians did have a difference flexion angle during squatting; since the ability to reach high flexion is equal, and the Frequency of High Flexion questionnaire had equal scores, it was concluded that East Asians may have had an unexplained cultural exposure that was not expressed as practice based on the questionnaire (for example, Canadian East Asians may have seen the flat foot squatting pose performed by their family members or on cultural media so although the participants may not have practiced the pose on a regular basis, they may have had a better strategy for achieving high flexion through imitation).

Although no difference in the ability to achieve a high knee flexion angle was found between ethnicites, an unexpected difference in knee flexion moment between Canadian East Asians and Caucasians was discovered. During descent, ascent, and static holds for both kneeling and squatting, Canadian East Asians had a significantly higher flexion moment. Although many different factors may contribute to this overall effect, the majority of difference seen during squatting was explained by the difference in tibial position with respect to the global coordinate system. East Asians had a tendency to exhibit tibial orientations closer to horizontal (by increasing ankle plantarflexion), which likely created a longer moment arm from the ankle to the body's center of mass. During kneeling, the major difference between ethnicities appears to be temporal; the Canadian East Asians have a greater proportion of people who experience their peak flexion moment during a true transition, which is a higher value than the static kneeling. In contrast, the majority of Caucasians reach their peak knee flexion moment during full flexion, or minutely before which lowers the overall average moment seen.

The third and final purpose of this research was to determine if kinetic differences existed between different styles of kneeling and squatting. For comparisons, two styles of kneeling and two styles of squatting were chosen, based on styles commonly seen in East Asian cultures or Western North American cultures. The East Asian styles chosen were the flat foot squat and the plantarflexed kneel, while the Western styles were the heels raised squat and the dorsiflexed kneel. The two squatting styles and two kneeling styles were compared with each other with the intent of determining if one style of kneeling or squatting may produce lower moments of force at the knee joint in order to reduce injury risk (Pollard et al., 2011). The two different kneeling styles were found to be no different, although a higher adduction and flexion moment is experienced in the lead leg, which indicates that if one leg is injured or more at risk, that leg should be used as the trail leg when transitioning into kneeling. The two styles of squatting however were quite different. The flat foot squat produced a significantly lower flexion and adduction moment in comparison to the heels raised squat which implies that when possible, a flat foot squatting pose should be used to reduce the moments of force at the knee.

The results of this study should be used as a platform for future work into differences between ethnicities, along with greater exploration between styles of squatting and kneeling during a much longer static hold. This study used an 8 second static hold, which is not comparable to the way most East Asians use high flexion for ADLs (eating, relaxation, toileting; all of which take longer than 8 seconds). In this study, the majority of participants found the high flexion postures to be fairly passive (with the exception of one or two muscles in each pose – such as tibialis anterior during flat foot squatting – generally fewer than 15% of participants had active muscles), but a longer exposure may change the muscular activity level as participants get uncomfortable and fidget or use muscular effort to unload the joint (which cannot be measured directly).

This study has produced several novel outcomes within the field of high flexion knee research and has begun a hitherto unexplored area of kinetic ethnicity comparison research within high flexion. It is anticipated that the outcomes from this research will be directly used for recommendations with respect to preferred styles of squatting, recommendations to avoid excessive joint loading on a compromised leg, and to establish that East Asian and Caucasians do not have a difference in ability with respect to the ability to achieve high flexion angles. It is anticipated that the outcomes from this research will be indirectly used as a platform for further work comparing ethnicities with respect to TKA requirements and improvements to existing designs, as well as future work examining long term effects of different kneeling and squatting styles. Kneeling and squatting are considered ADLs for many individuals, whether from a cultural or occupational standpoint, which makes expanding the limited field of high flexion research a valuable pursuit for the immediate future.

10. References

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11. Appendices

Appendix A

Frequency of High Flexion questionnaire

The questionnaire will be given to participants electronically- therefore, formatting may differ.

Participant ID_____________________________. Date_____________________________.

Thigh Circumference___________________(cm) Calf Circumference__________________(cm)

Weight_____________________________(kg) Height_____________________________(m)

Age________________________________(years)

How many months have you spent living in Canada/United States/Europe in your lifetime?

How many months have you spent living in China/Japan in your lifetime?

How many months have you spent living elsewhere? Please specify.

If you were born in China or Japan, and have been living in North America for less than 2 years, please answer the following questions based on living in China or Japan, and then REPEAT the questionnaire with current information

1. What ethnicity best describes you? Score

Chinese, raised in China

Chinese, raised in Canada

Japanese, raised in Japan

Japanese, raised in Canada

Korean, raised in Korea

Korean, raised in Canada

Vietnamese, raised in Vietnam

Vietnamese, raised in Canada

Caucasian, born in Canada

2. Do you ever use a squat, or Eastern style, toilet?

No, never	0
Occasionally when I'm using a public toilet	1
Yes, my home has a squat toilet	3

3. Do you kneel for religious purposes?

No, never	0
Only on holy days	1
At least once per day	2
Other:	

4. Do you kneel as a rest posture, such as while eating, drinking, or socializing?

No, never	0
Sometimes (ex. Playing with a small child)	0.5
Yes, often	2

5. Does your occupation require kneeling or squatting on a regular

basis?

No, never	0
Yes, but rarely	0.5
Yes, I often kneel or squat at work (more than once per day)	3

6. Do you ever squat as a rest posture, such as while outdoors to avoid sitting on the ground?

No, never	0
Sometimes- maybe once per month	0.5
Sometimes- at least once a week	1
Often- most days	2

7. How many hours per day do you think you spend squatting and/or kneeling?	1 hour = 1 point

Appendix B

Supporting Figures

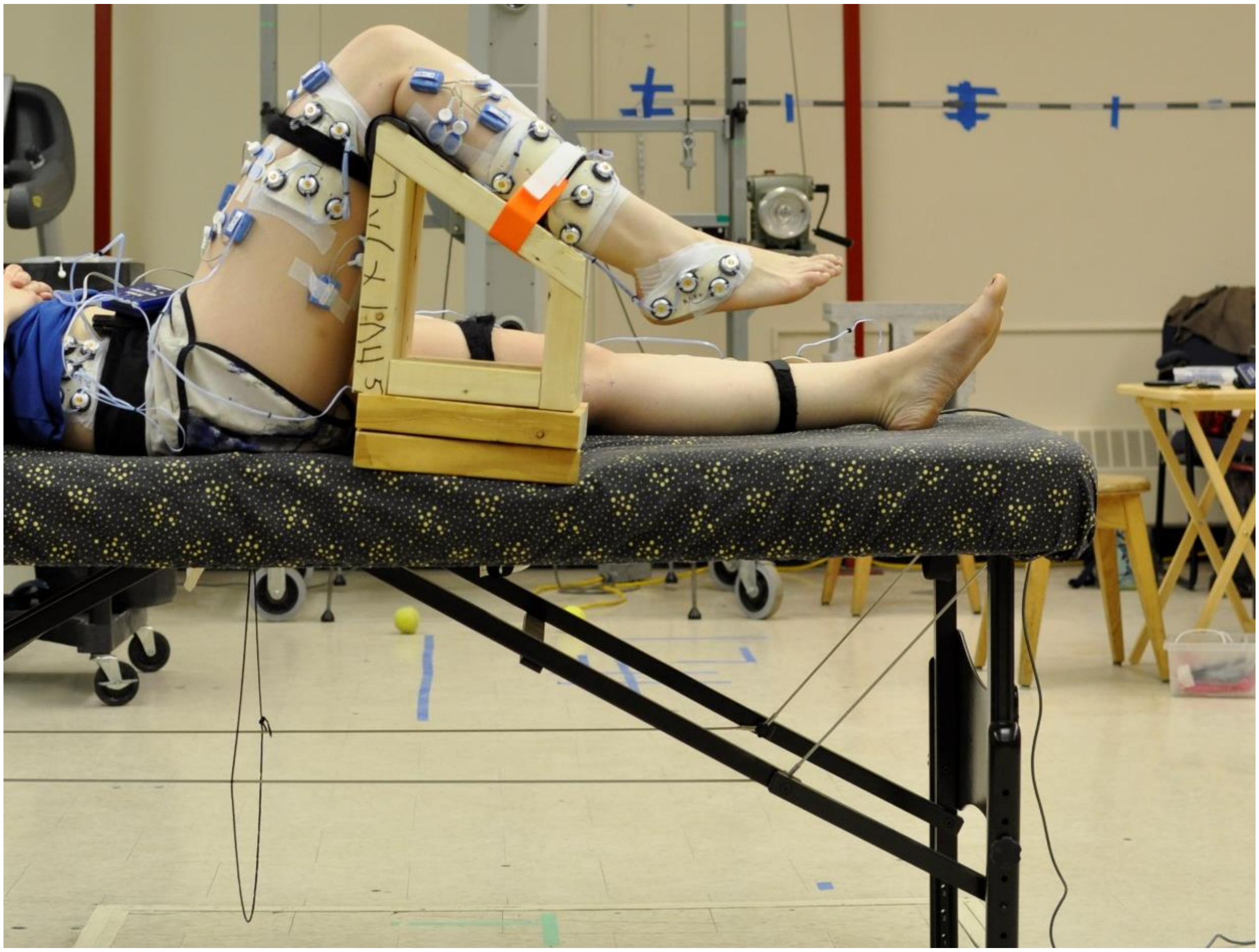

Figure B.1 PROM knee jig; the participant's leg is held at approximately 30° flexion to ensure that the gastrocnemius muscle length is not changing as a result of knee flexion angle mid trail.

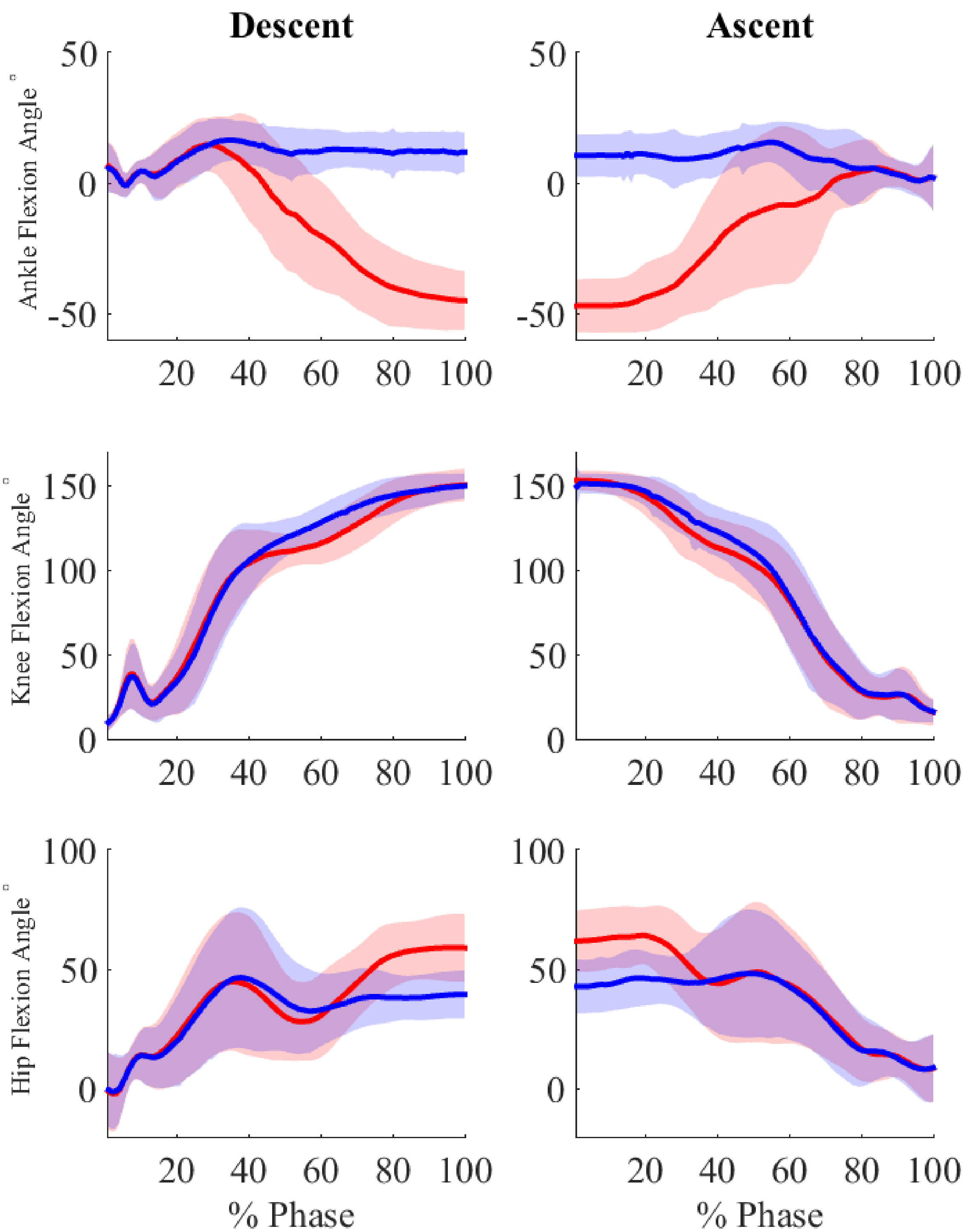

Figure B. 2 Lead leg kinematics during both kneeling styles. Plantarflexed kneeling is represented in red, and dorsiflexed kneeling is represented in blue. All participants were included, n=43. The bold line represents the group mean, and the shaded areas represent ±1 SD.

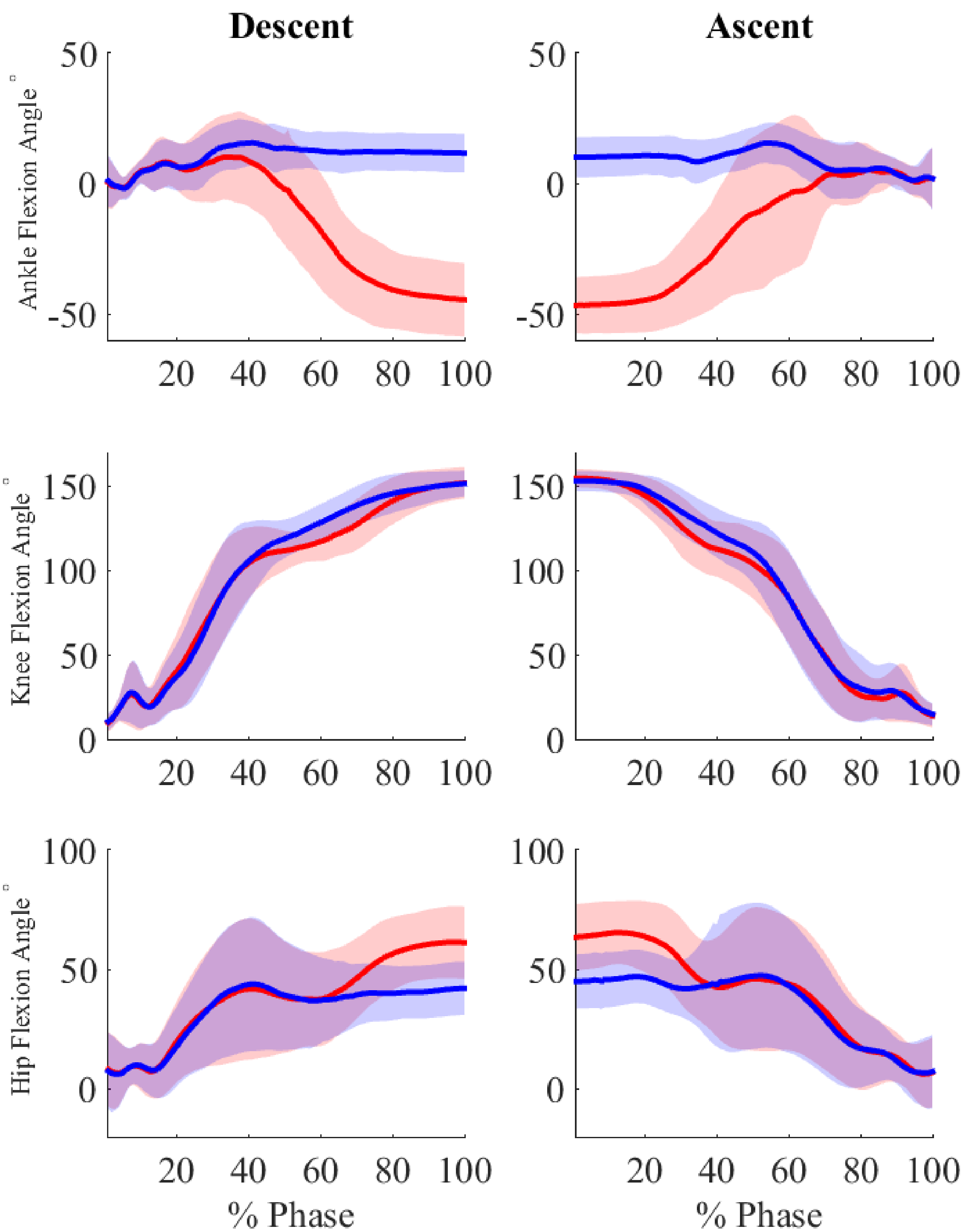

Figure B. 3 Trail leg kinematics during both kneeling styles. Plantarflexed kneeling is represented in red, and dorsiflexed kneeling is represented in blue. All participants were included, n=43. The bold line represents the group mean, and the shaded areas represent ±1 SD.

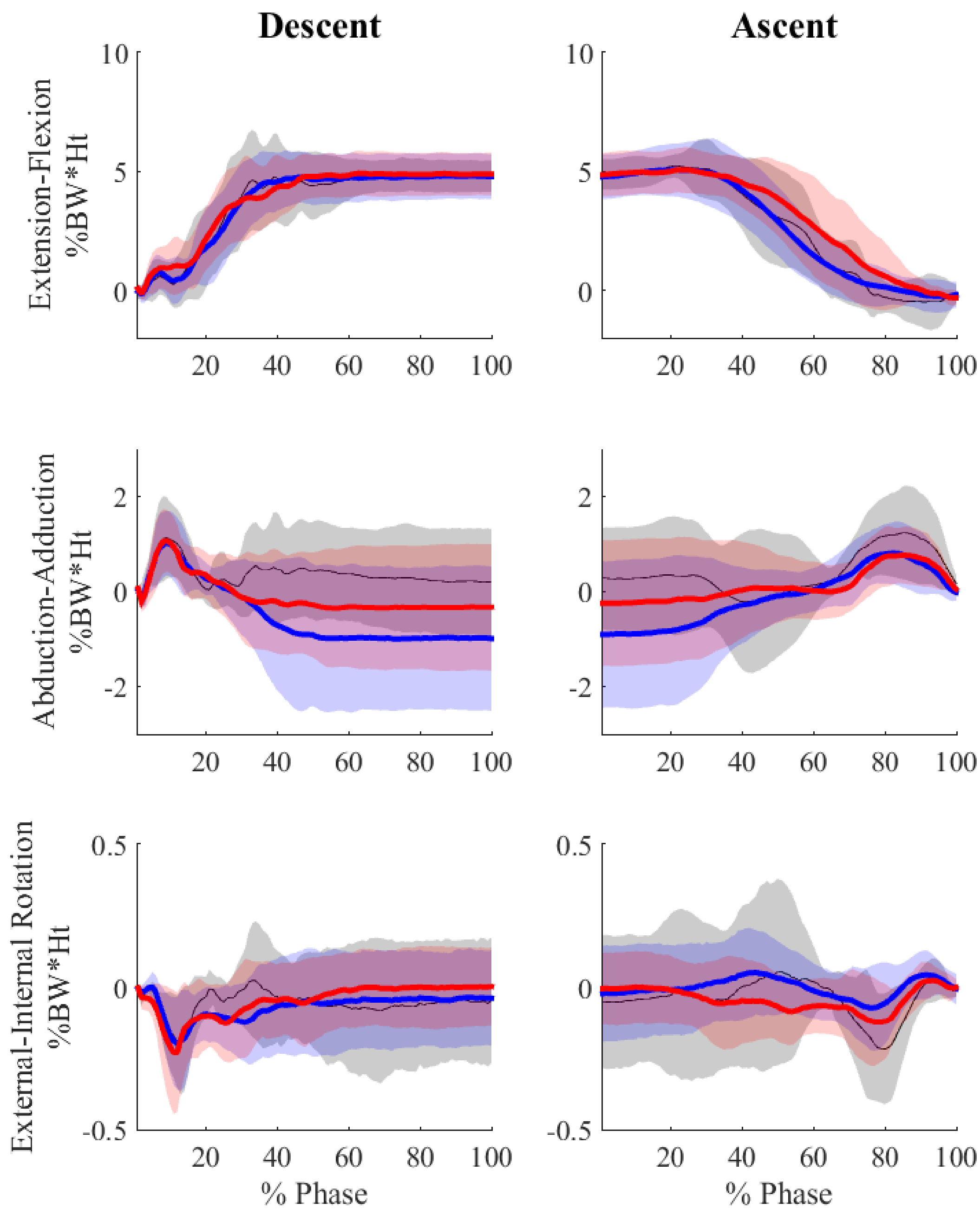

Figure B. 4 Knee moments (flexion, adduction, and rotation) during flat foot squatting. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.

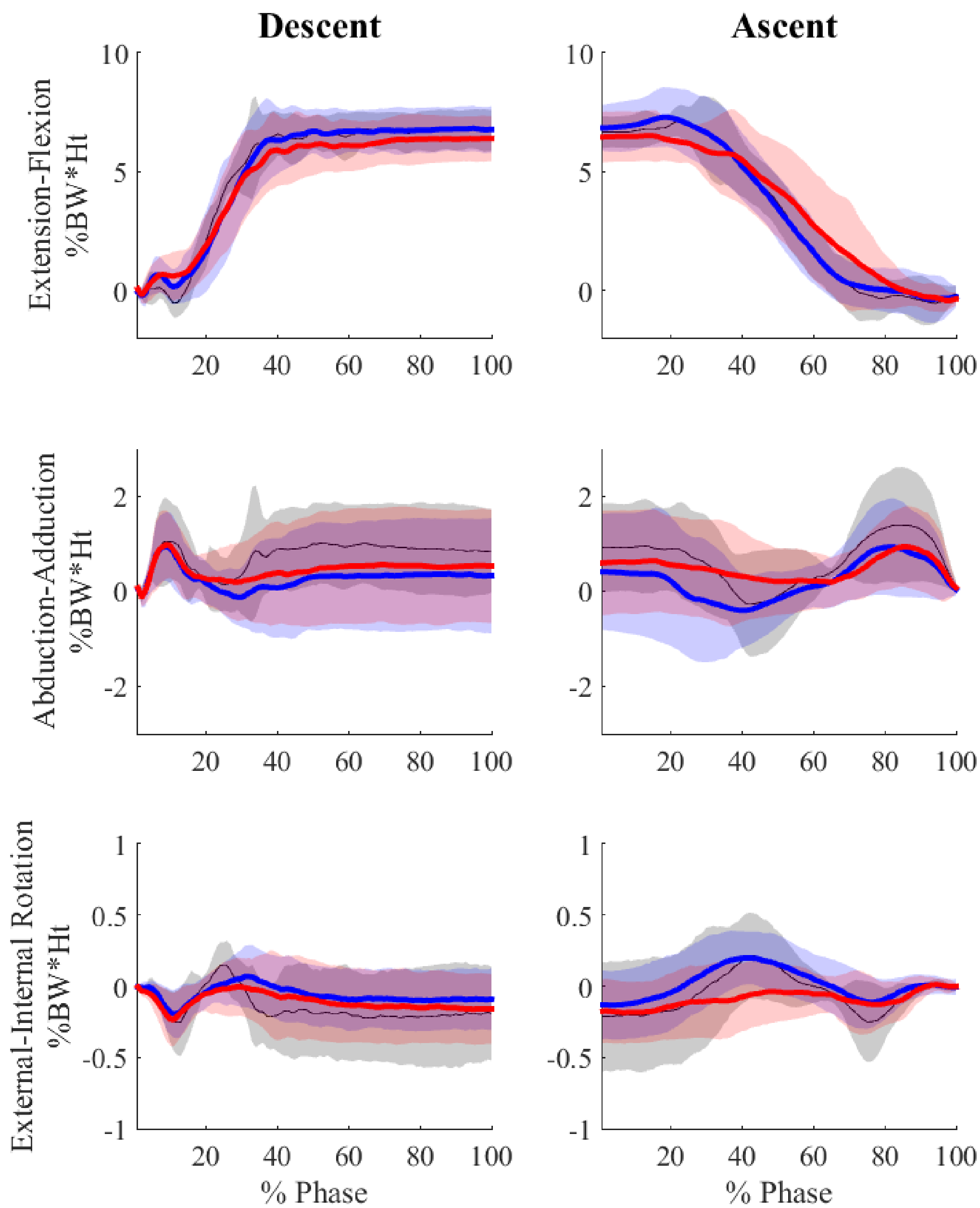

Figure B. 5 Knee moments (flexion, adduction, and rotation) during heels raised squatting. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.

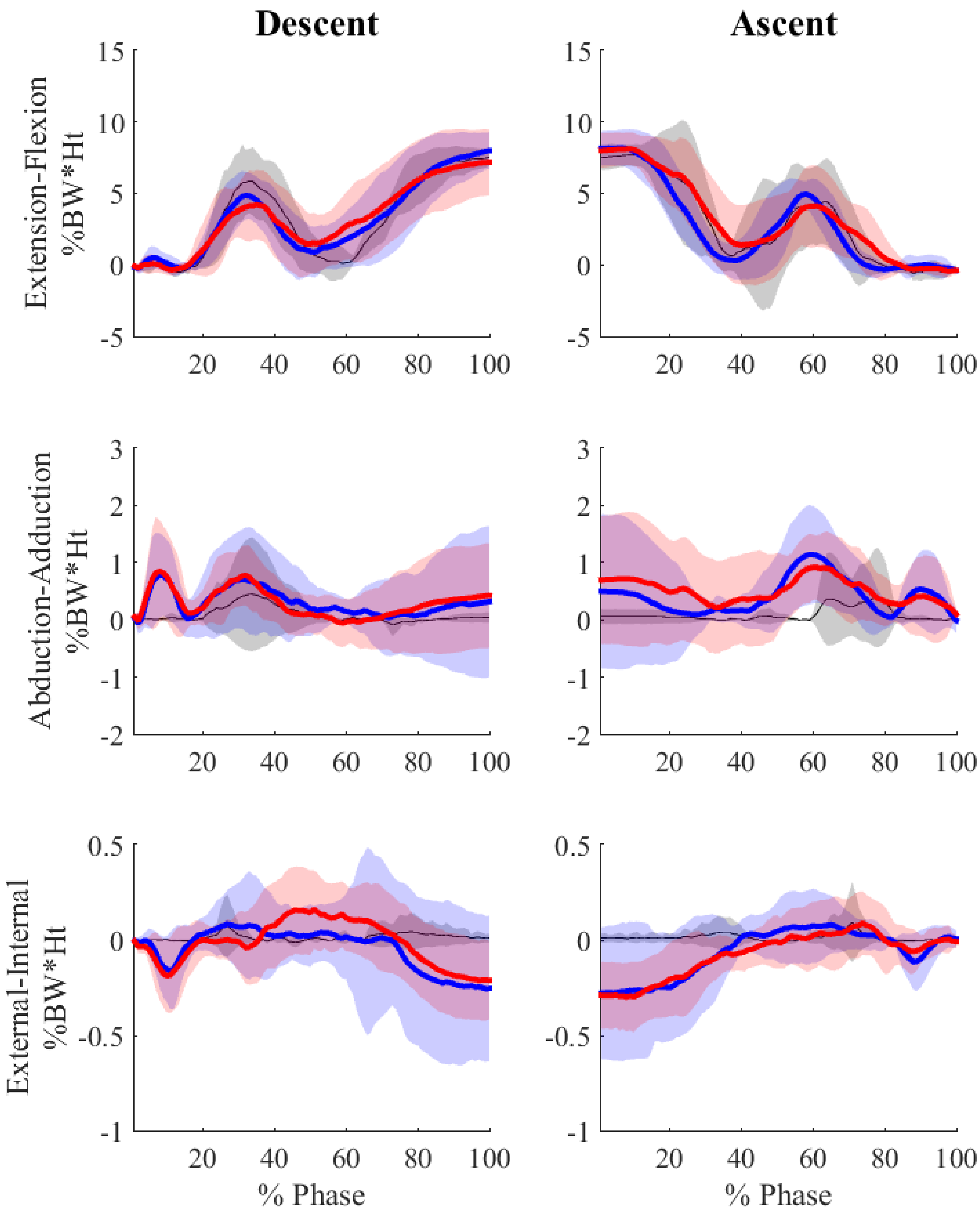

Figure B. 6 Lead knee moments (flexion, adduction, and rotation) during plantarflexed kneeling. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.

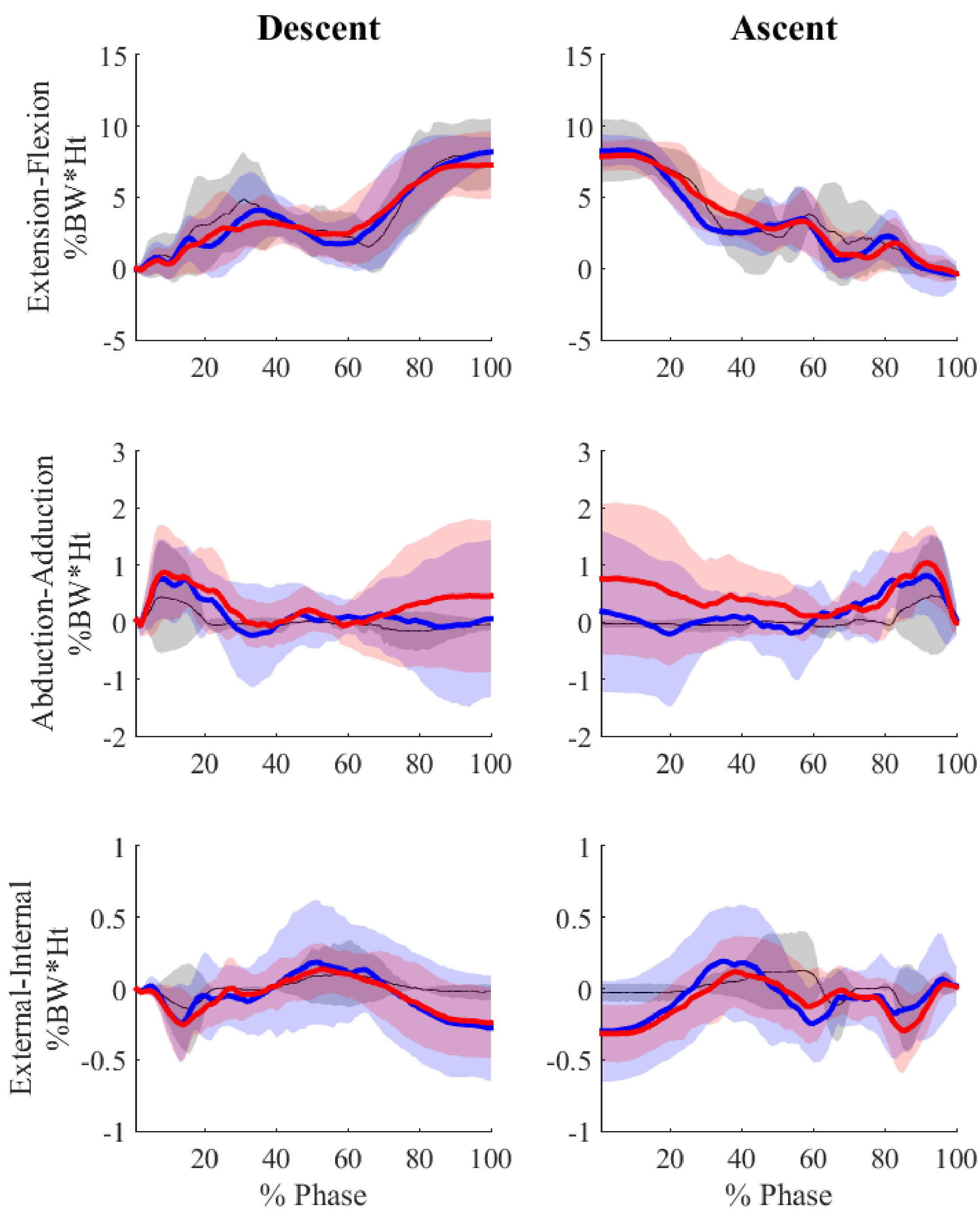

Figure B. 7 Trail knee moments (flexion, adduction, and rotation) during plantarflexed kneeling. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.

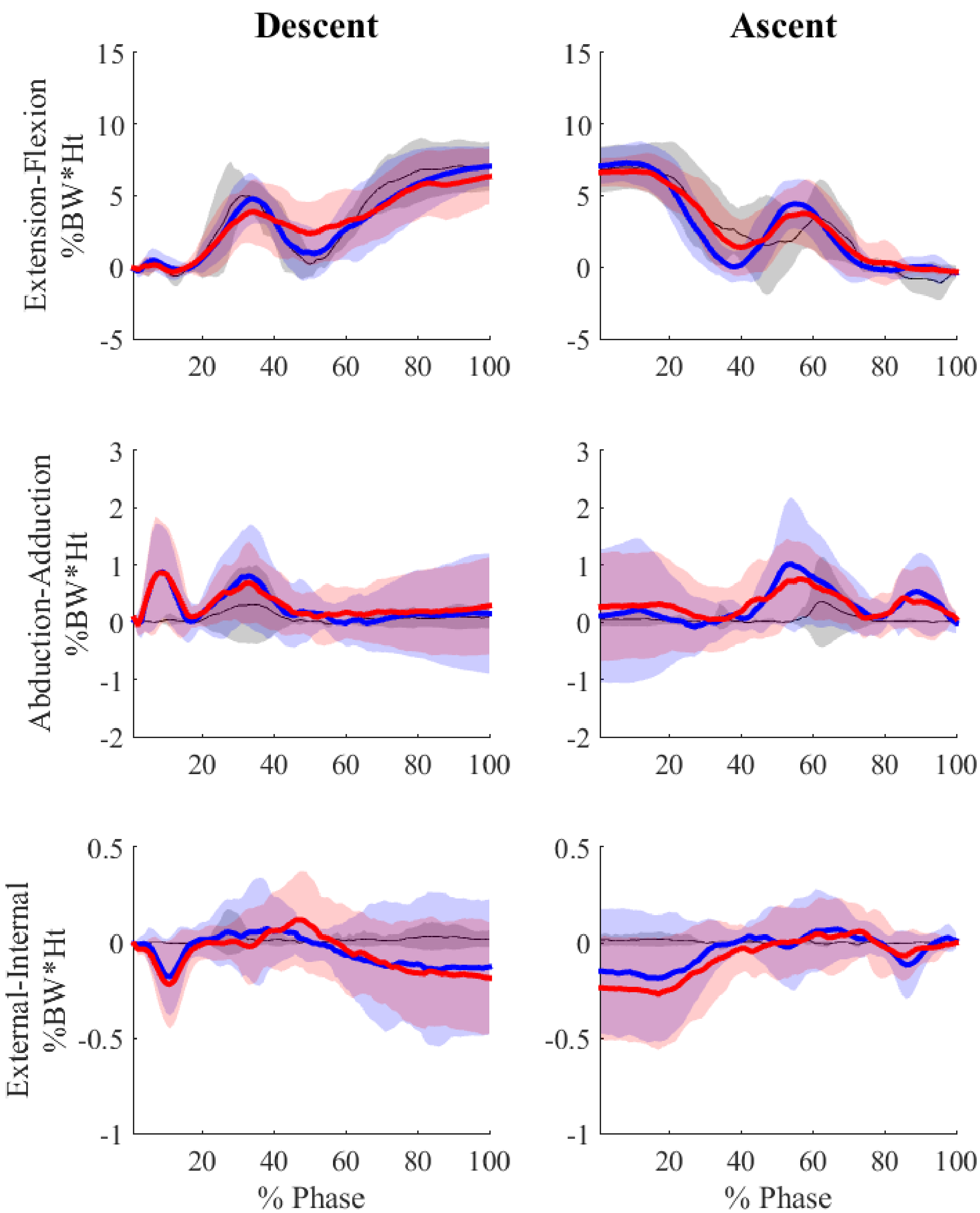

Figure B. 8 Lead knee moments (flexion, adduction, and rotation) during dorsiflexed kneeling. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.

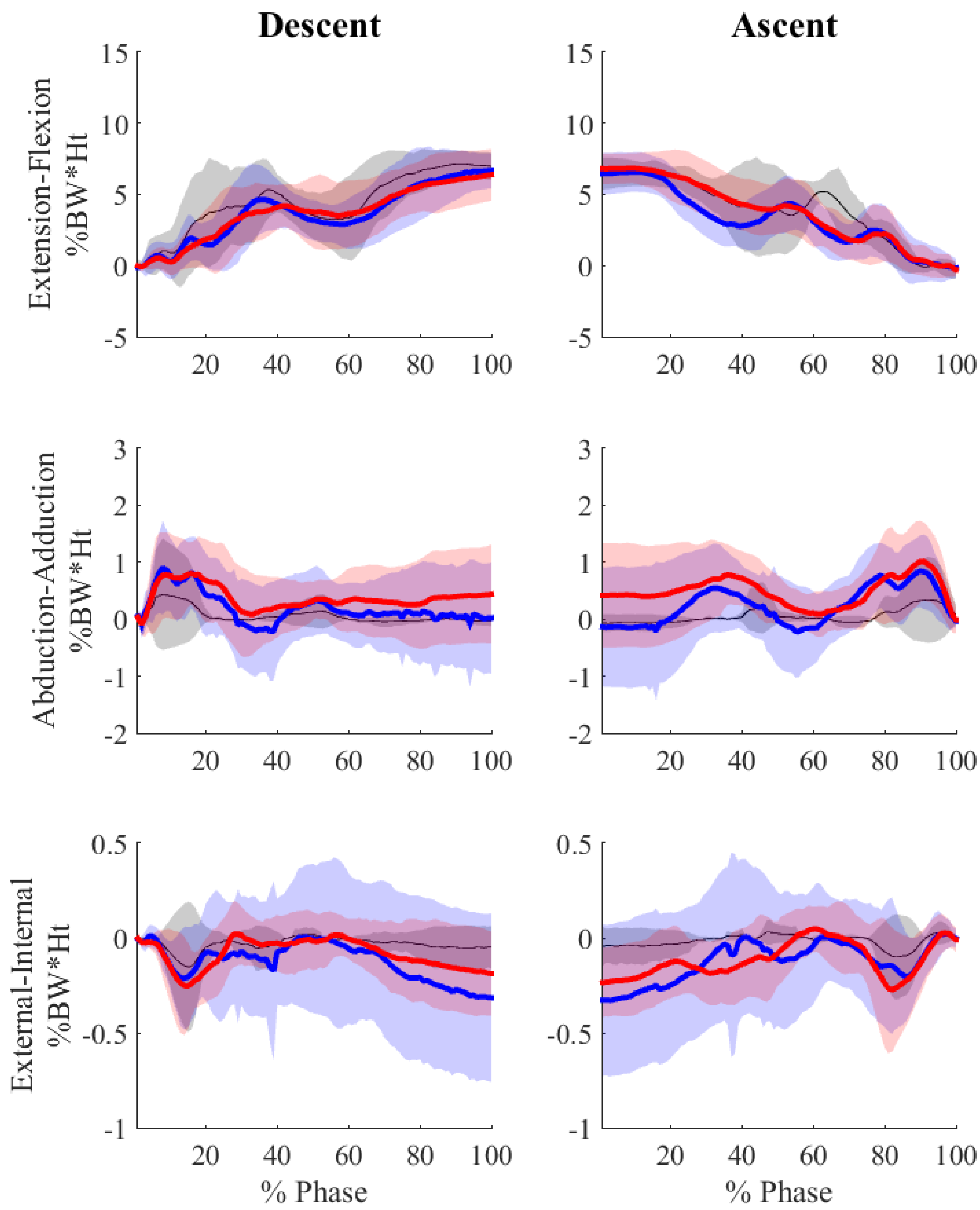

Figure B. 9 Trail knee moments (flexion, adduction, and rotation) during dorsiflexed kneeling. Caucasians are represented in blue, Canadian East Asians are represented in red, and East Asians are represented in black. The bold line represents the group mean, and the shaded areas represent ±1 SD.