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Differences Between the Sexes in Knee Kinetics During Landing from Volleyball Block Jumps

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Title: Gender differences in knee kinetics during landing from volleyball block jumps.

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Abstract.

The purpose of the study was to investigate gender differences in frontal and sagittal plane kinetics (normalised ground reaction force and normalised knee moment) in university volleyball players when performing opposed block jump landings. Females displayed a significantly lesser normalised knee extension moment at the start of muscle latency than males. The greater normalised knee extension moment at the start of muscle latency in females suggests that through practise, the female subjects may have developed a landing strategy that minimises the moment acting about the knee in the sagittal plane to reduce the likely strain on the passive support structures. The time histories of the normalised knee moment in the frontal plane were different between males and females. The maximum normalised knee valgus moment was significantly greater in females than males. The significantly different maximum normalised knee valgus moment between males and females indicates greater likelihood of overloading the muscles of the knee in females during landing which in turn is likely to increase the strain on the passive support structures. The increased likely strain on the passive support structures of the knee in females could contribute to the reported greater incidence of non-contact ACL injury in females compared to males.

Introduction.

Research suggests that between 70% and 90% of anterior cruciate ligament (ACL) injuries occur in non-contact situations (Griffin, et al., 2000; McNair, Marshall, & Matheston, 1993; Mykelbust, Maehlum, Engbretsen, Strand, & Solheim, 1997), i.e., no direct contact with the knee at the time of injury. ACL injury appear to occur most frequently during movements such as landing (Hopper & Elliot, 1993), deceleration (Miller, Cooper, & Warner, 1995) or rapid change of direction (Olsen, Mykelbust, Engebretsen, & Bahr, 2004). The incidence of ACL injury is therefore high in sports involving a high frequency of landing, decelerating and rapid changes of direction (e.g. basketball, netball, handball and volleyball) (Arendt & Dick, 1995; Griffin et al., 2000). The incidence of non-contact ACL injury has been reported to be 6 to 8 times greater in females than in males competing in the same sports (Arendt & Dick, 1995; Chandy & Grana, 1985; Ferretti, Papandrea, Conteduca, & Mariani, 1992; Gray et al., 1985; Gwinn, Wilckens, & McDevitt, 2000; Lidenfeld, Schmitt, & Hendy, 1994; Malone, Hardaker, & Garrett, 1993). A number of potential risk factors have been proposed to account for this gender difference in the incidence of non-contact ACL injury. These include intercondylar notch width (Ireland, Balantyne, Little, & McClay, 2001), Q angle (Shambaugh, Klein, & Herbert, 1991), patella tendon tibia shaft angle (Nunley, Wright, Renner, Yu, & Garrett, 2003), ACL cross sectional area (Charlton, St John, Ciccotti, Harrison, & Scheitzer, 2002), joint laxity (Uhorchak et al., 2003), hormonal influences (Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002), muscle strength (Salci, Kentel, Heycan, Akin, & Korkusus, 2004), muscle stiffness (Wojtys, Huston, Shock, Boylan, & Ashton-Miller, 2003), muscle activity patterns (Zeller, McCrory, Ben Kibler, & Uhl, 2003) and biomechanics of landing (Chappell, Yu, Kirkendall, & Garett, 2002; Salci et al, 2004; Yu, Lin, & Garett, 2006; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Decker, Torry, Wyland, Sterett, & Steadman, 2003). However, the only evidence (uni-variate correlation based on small samples) in support of gender differences with regard to some risk factors, such as Q angle, joint laxity, intercondylar notch width, ACL cross sectional area and hormones, is fairly weak. The evidence in support of gender differences with regard to some of the factors affecting the dynamic stability of the knee, in particular gender differences in landing biomechanics (Chappell et al., 2002; Salci et al., 2004; Yu et al., 2006; Kernozek et al., 2005) is much stronger.

During landing the ankle, knee and hip joints will move from a position of relative extension to flexion as the downward linear momentum of the body is reduced to zero. These joint movements are determined by the net moments acting about the joints. It takes a certain amount of time (latency period of the muscles) for the muscles to fully respond to the ground reaction force (GRF). Muscle latency varies between 30 ms and 75 ms (Nigg et al., 1984; Watt & Jones, 1971). Whilst muscle activity prior to landing may play a role, for changes in external load that occur in less than the latency period of muscles the body is forced to respond predominantly passively to the external load. During this period of passive loading, the body is vulnerable to injury from high forces within the tissues of the joint that occur as a result of high GRF and/or high external moments about the joints arising from the GRF. After the passive loading phase, the magnitude and direction of the GRF is primarily controlled by conscious muscular activity, referred to as the active loading phase. During active loading, the muscles primarily determine the magnitude and direction of the GRF in order to try to prevent substantial GRF moments about the lower limb joints and therefore reduce the risk of injury. It is, perhaps, not surprising that ACL injury appears to occur most often just after initial ground contact (Boden, Dean, Feagin, & Garett, 2000; Olsen et al., 2004), i.e. during passive loading.

Studies examining knee moments and GRF during landing indicate that females tend to exhibit greater normalised peak knee extension moment (Chappell et al., 2002; Salci et al., 2004; Yu et al., 2006) and greater normalised peak GRF (Kernozek et al., 2005; Salci et al., 2004; Yu et al., 2006) than males. There is very little empirical data available on knee moment in the frontal plane during landing. Chappell et al. (2002) found females to display greater normalised knee valgus moment than males, whereas Kernozek et al. (2005) found females to display lower normalised knee varus moment than males in landing manoeuvres.

However, lack of appropriate standardisation in task demands may have invalidated meaningful comparison between females and males. For example, dropping down from a raised platform set at the same height for both males and females (Decker et al., 2003; Salci et al., 2004; Kernozek et al., 2005) may result in significantly different task demands. To our knowledge, no study has examined gender differences in knee kinetics when performing sport specific tasks with the inclusion of opposition. Table 1 shows the results of a number of studies that have reported group mean data for ground reaction force and moment about the knee in landing manoeuvres.

Table 1 about here.

The greater the external moment (moment due to the GRF during landing) about the knee joint axis the greater the resultant moment about the knee joint is likely to be and therefore, the greater the risk of overloading the muscles about the knee joint. Since knee joint stability (i.e., prevention of abnormal joint movement) is maintained by dynamic (contractile) and passive (non-contractile) support structures, the greater the load on the muscles, i.e. dynamic support structures, the greater the extent to which stability of the knee joint is likely to be maintained by the passive support structures, in particular the ACL, posterior cruciate ligament (PCL), lateral and medial ligaments. If the load on the passive support structures exceeds their strength, injury is likely to occur. Consequently, the reported increased incidence of ACL injury in females during landing movements may be due, in part, to greater peak normalised knee extension moment and greater normalised ground reaction force. Further investigation is needed concerning the influence of moments in the frontal plane during landing/cutting on the gender difference in the incidence of non-contact ACL injury.

The aim of the study was to investigate the effects of gender on knee kinetics in university volleyball players performing block jump landings in opposed conditions. It was hypothesised that males and females would display different knee joint moments and GRF in the sagittal and frontal planes during landing from volleyball block jumps which may be indicative of a greater likelihood of ACL injury in females compared to males.

Method.

Subjects.

Six female (Mean age 21.7 ± 1.5 years, mass 58.1 ± 6.2 kg and height 165.2 ± 7.1 cm) and six male (Mean age 22.2 ± 2.6 years, mass 72.1 ± 4.5 kg and height 177.1 ± 9.4 cm) university volleyball players participated in the study. All subjects were right leg dominant and had no previous history of hip, knee or ankle injury. Ethical approval was granted for the study by the University Ethics Committee and written consent forms were signed by all subjects prior to data collection.

Measurement system.

An AMTI force platform sampling at 600 Hz was used to measure the GRF and the location of the centre of pressure acting on the right leg during landing. A time synchronised 12 camera Vicon 512 system (Vicon, Oxford, England) sampling at 120 Hz was used to determine 3D coordinates of 8 retro-reflective markers (25 mm diameter). Markers were placed directly on the skin of each subject’s right (dominant) leg in accordance with the Vicon system’s lower body plug-in gait marker set. All subjects wore tight fitting clothing in order to minimise marker occlusion. The marker locations were: anterior superior iliac spine, posterior superior iliac spine, lower lateral surface of the thigh along the line between the hip and knee joints, lateral epicondyle of the femur, lower lateral surface of the tibia along the line between knee and ankle joints, lateral malleolus of the ankle, superior proximal end of the second metatarsal, posterior aspect of the Achilles tendon at the same height as the second metatarsal marker. From the location of the markers placed on the body, combined with required anthropometric measurements of each subject entered into the system, the Vicon system calculated the 3D coordinates of hip, knee and ankle joint centres. The subject anthropometric measurements required were height, weight, leg length, knee width and ankle width. The Vicon system uses the Newington-Gage model to define the positions of the hip joint centres within the pelvis segment (in which pelvis size and leg length are used as scaling factors) in conjunction with the markers placed on the pelvis and leg length measurement to determine the 3D position of hip joint centre (Davis, Ounpuu, Tyburski, & Gage, 1991). The knee joint centre is determined from hip joint centre, knee marker, thigh marker and knee width measurement. The ankle joint centre is determined from the knee joint centre, ankle marker, tibia marker and ankle width measurement.

Angular definitions.

In the Plug-in gait system, the measurement of knee flexion/extension is based on the thigh axis (line connecting the hip joint and knee joint centres) and the shank axis (line connecting the knee and ankle joint centres) projected onto the plane of knee flexion/extension (as determined by the plug-in gait marker system). The flexion/extension angle is the angle between the distal extension of the thigh axis and the shank axis. A positive angle corresponds to knee flexion relative to the fully extended position. The measurement of knee valgus/varus is based on the thigh axis and the shank axis projected onto the plane of knee valgus/varus (defined as perpendicular to the knee flexion/extension axis). The valgus/varus angle is the angle between the distal extension of the thigh axis and the shank axis. A positive angle indicates varus and a negative angle indicates valgus.

Moment definitions.

The inverse dynamics approach to calculating the moments acting about a joint is the most accurate method as it takes into consideration all of the possible component moments. However, when the segment mass is small and the linear and angular accelerations of the segment centre of gravity are small relative to external moment, the more closely the external moment will approximate the moment acting about a joint (Winter, 1990). When this is the case, the quasi-static model for calculating the joint moment is justifiable (Alexander & Vernon, 1975; Harrison, Lees, McCullagh, & Rowe, 1986; Hewett, Stroupe, Nance, & Noyes, 1996; Smith, 1975). Alexander and Vernon (1975) found that in two 68 kg male subjects landing from a 0.81 m vertical drop the effect of the segment mass and the linear and angular accelerations of the segment centre of gravity were small in relation to external moment (moment due to the GRF) when calculating the moment about the knee joint centre. For example, during landing the peak moment about the knee was estimated at 120 N.m using the quasi-static model which was decreased by 9 N.m when segment mass and the linear and angular accelerations of the segment centre of gravity were included. Therefore, the quasi-static model was used to estimate the moment about the knee joint centre of the right leg in the sagittal and frontal planes during landing.

The GRF moment was calculated using the cross product $\boldsymbol{r} \times \boldsymbol{F}$ where $\boldsymbol{r}$ = position vector of the point of application of F (centre of pressure) with respect to the knee joint centre and $\boldsymbol{F}$ = ground reaction force vector. In the sagittal plane, a GRF moment that tends to extend the knee, using the quasi-static approach, is considered to be equal and opposite to a corresponding knee flexion moment. Similarly, a GRF moment that tends to flex the knee results in a corresponding knee extension moment. In the frontal plane, a GRF moment that tends to adduct the knee (move into a varus position), using the quasi-static approach, is considered to be equal and opposite to a corresponding knee valgus moment. Similarly, a GRF moment that tends to abduct the knee (move into a valgus position) results in a corresponding knee varus moment.

Landing Task.

Prior to data collection all subjects performed a 10-min warm up consisting of lower limb stretching and running/jogging on a treadmill at self determined speeds. When this was completed, subjects practised the jumping and landing task until comfortable with the procedure. Whilst previous studies have examined gender differences in knee kinetics during landing from vertical drops from standardised heights without the inclusion of opposition (Decker et al., 2003; Salci et al., 2004; Kernozek et al., 2005), in the present study, the jumping and landing task was made as realistic as possible by having subjects attempt to block an actual spike performed by an experienced volleyball player in an attempt to improve the ecological validity of the data obtained. To do this, a rope fixed horizontally 5 cm in front of the force platform to act as a volleyball net at a height of 2.43 m for male subjects and 2.24 m for female subjects (height of a standard volleyball net). Also, a volleyball was suspended from the ceiling and positioned with the bottom of the ball 5 cm above the net (2.48 m for males and 2.29 m for females) and with the centre of the ball 10 cm in front of the line of the net (the other side of the net to where the subject (blocker) was standing). At the start of each trial, the subject stood with their right foot on the force platform. The subject then timed his/her blocking action in order to try to block the ball as it was spiked. The ball was spiked from the same suspended position in order to eliminate variation in the position and velocity of the ball. On landing, only the right foot landed on the force platform and trials where the right foot did not land entirely on the force platform were discarded. Data was recorded for three successful trials for each subject.

Data analysis.

The 3D coordinate data were filtered using a Woltring Filter. To alter the filter settings a mean squared error (MSE) tolerance value was entered into the Vicon system. The MSE method allows the noise level to be input and a spline function is fitted to the data points in accordance with the specified level of tolerance. Consistent application of this processing method ensured the same level of smoothing for all marker trajectories. Based on a primary consideration of minimising high frequency artefacts whilst maintaining the detail of the signal at all lower frequencies, it was determined that it would be most appropriate to use a MSE value of 50 as a suitable setting for filtering the data. This was determined by analysing the effects of a number of different filter settings for sample data of a number of different jumps and from a number of different subjects. In determining a suitable MSE value, the data were analysed using a Welch periodogram to provide power spectral density (PSD) plots that quantify the magnitude of power in a narrow frequency band (in this case the bandwidth was 1/120 Hz). From the PSD plots, the estimated frequency of the start of signal attenuation, 50% of signal attenuation and almost complete signal attenuation could be determined for the MSE value of 50. The filter setting determined to be most appropriate for these data (i.e. MSE = 50) corresponded to a low-pass filter of cut-off frequency 10 Hz and stop-band frequency of 30 Hz.

The GRF, knee angle and the knee moment in the sagittal (flexion/extension) and frontal (valgus/varus) planes were determined between initial ground contact (IC) and, depending on which occurred later in the trial, either maximum knee flexion or maximum knee valgus/varus angle (MAX) in each trial. All data were then normalised with respect to average trial time. Figures show variables plotted against normalised time and against absolute mean trial time between IC and MAX. Absolute mean contact time was 0.190 s ± 0.040 for males and 0.194 s ± 0.057 for females. As there was no significant difference between contact time for males and females, mean contact time of 0.192 s was used. GRF was normalised to body weight (in Newtons) and knee moments were normalised to body weight (in Newtons) and height (in metres). Mean data were based on 18 trials for males (6 subjects × 3 trials × 1 leg) and 18 trials for females (6 subjects × 3 trials × 1 leg). Independent-samples t-tests were carried out on the GRF, knee angle and moment about the knee data in the sagittal and frontal planes at the start of the muscle latency period (ML) (0.03 s), the start of the active loading period (AL) (0.075 s), at MAX and minimum and maximum values to examine gender differences. Due to multiple t-tests being carried out on samples taken from the same population, to reduce the chance of type I error, a Bonferroni adjustment was made to the alpha level.

Results.

Group mean curves for normalised GRF, knee angle and normalised knee moment (+ve = flexion moment, – ve = extension moment) throughout the landing period in the sagittal plane for males and females are shown in Figure 1. With regard to normalised GRF (Figure 1a), the overall shapes of the curves were similar for males and females, i.e. increase during the passive loading phase (PP) (IC to 0.075 s) followed by decrease during the active loading phase (AP) (0.075 s to MAX). For most of the landing period, the normalised GRF was greater for males than females. The main difference between males and females occurred during PP where females exhibited a smaller initial peak which also occurred earlier in the landing phase than in males. There was no significant difference between males and females' normalised GRF at ML, AL, MAX or maximum normalised GRF (Table 2).

Figure 1 about here.

Table 2 about here.

Females and males exhibited a progressive increase in knee flexion during the landing phase (Figure 1b). Females exhibited significantly greater MAX knee flexion (Table 2). There was no significant difference in knee flexion angle between males and females at ML or AL.

During PP, females exhibited a smaller peak in normalised knee extension moment than males, which occurred earlier during the landing phase in females than in males (Figure 1c). During AP, the normalised knee extension moment was very similar in males and females. Females displayed a significantly smaller normalised knee extension moment at ML than males. There was no significant difference in the normalised knee extension moment between males and females at AL, at MAX or the maximum and minimum values (Table 2). The magnitude of the standard deviation of the normalised knee moment data at 1% normalised time intervals was very similar between IC and MAX in males and females (Figure 1c). Mean stick figures of the angle of the knee and the normalised GRF vector in the sagittal plane for males and females at ML, AL and MAX are shown in Figure 2.

Figure 2 about here.

Group mean curves for normalised GRF, knee angle and normalised knee moment (+ve = valgus moment, –ve = varus moment) in the frontal plane throughout the landing period are shown for males and females in Figure 3. Since Fy (mediolateral force) and Fx (anterioposterior force) were small relative to Fz (vertical force) during landing, the resultant normalised GRF in the frontal plane (Figure 3a) was very similar to the resultant normalised GRF in the sagittal plane. Therefore as with the resultant normalised GRF in the sagittal plane, the resultant normalised GRF in the frontal plane was similar in shape in males and females, was greater for males than females during most of the landing phase and the main difference between males and females occurred during PP where females exhibit a smaller initial peak which occurred earlier in the landing phase than in males. There was no significant difference between males and females' normalised GRF at ML, AL, MAX or maximum GRF (Table 3).

Figure 3 about here.

Table 3 about here.

In the frontal plane, females tended to contact the ground with the angle of the knee in a valgus position (–ve values) which progressively increased between IC and MAX. In contrast, males tended to contact the ground in a valgus position and maintained a valgus position throughout the landing phase (Figure 3b). The amount of valgus at ML and AL were not significantly different between males and females. However, the maximum knee valgus angle was significantly greater in females compared to males (Table 3).

The normalised knee moment (Figure 3c) remained in valgus throughout the landing phase for females, with an increase in normalised knee valgus moment during PP and a decrease during AP. However, for males, the normalised knee moment in the frontal plane was varus at IC, which increased then decreased until it changed to a valgus moment close to ML. The normalised knee moment in the frontal plane then changed back to varus at approximately 30% normalised time and remained in varus until MAX. At AL, the normalised knee varus moment in males was significantly different from the normalised knee valgus moment in females. The maximum normalised knee valgus moment was significantly greater in females than males. There was no significant difference in the normalised knee moment in the frontal plane at ML, MAX or maximum normalised knee varus moment between males and females (Table 3). The magnitude of the standard deviation of the normalised knee moment data at 1% normalised time intervals was very similar between IC and MAX. This is illustrated in Figure 3c. Mean stick figures of the angle of the knee and the normalised GRF vector in the frontal plane at ML, AL and MAX for males and females are shown in Figure 4.

Figure 4 about here.

Discussion.

Maximum normalised GRF in both the frontal and sagittal planes were not significantly different between females and males. This is different to a number of other studies which found females to exert greater normalised GRF than males when landing (Kernozek et al., 2005; Salci et al., 2004; Yu et al., 2006). This may be due to other studies having males and females dropping down from the same fixed height, whereas this study had subjects jumping up to block a ball at a height of 2.43 m for males and 2.24 m for females. It is unlikely females jump as high as males when playing those sports where non-contact ACL injury is particularly common, particularly volleyball as the net is 0.19 m higher for males than females. Also, in the present study, the GRF acting on the right leg was measured and not the combined GRF acting on the right and left legs as in previous studies (Kernozek et al., 2005; Salci et al., 2004; Yu et al., 2006).

The maximum normalised knee extension moment was not significantly different between females and males, contrary to a number of other studies (Chappell et al., 2002; Salci et al., 2004; Yu et al., 2006). This again may be due to differences in task demands and differences in subject playing standard between previous studies and the present study. The normalised knee extension moment at ML was significantly smaller in females than males. Also, the normalised knee extension moment was smaller in females than males during the majority of the landing phase. This suggests that through training, females may have developed a strategy of landing which minimises the moment acting about the knee in the sagittal plane in an attempt to reduce the likely strain on the dynamic and passive support structures of the knee. For the male and female groups, the maximum normalised knee extension moment in this study was very similar to that reported by Hewett et al., (1996). For example, values for the maximum normalised knee extension moment reported by Hewett et al., (1996) were 0.104 BW.ht for trained females and 0.158 BW.ht for untrained males compared to 0.110 BW.ht for trained females and 0.1325 BW.ht for trained males in the present study.

In males, the normalised knee moment in the frontal plane was small in comparison to females (Figure 3) and changed between valgus and varus during landing. In females however, the normalised knee valgus moment was greater than in males (Figure 3) and remained in valgus throughout the entire landing phase. At AL, the normalised knee varus moment in males was significantly different from the normalised knee valgus moment in females and the maximum normalised knee valgus moment was significantly greater in females than males. The greater maximum knee valgus moment in females indicates greater likelihood of overloading the muscles of the knee, in particular the muscles attached to the medial and lateral aspects of the tibia, such as the gracilis, semitendinosus, semimembranosus and biceps femoris. The greater loading of the muscles in females is therefore likely to indicate a greater possibility of strain on the passive support structures of the knee during landing in maintaining joint stability. Furthermore, the structure of the knee joint only allows one main degree of freedom, i.e. angular motion about a mediolateral axis (knee flexion/extension). The normal ranges of motion in the other five degrees of freedom (3 linear planes and 2 angular) are very small. Consequently, the quadriceps and hamstrings facilitate knee flexion and extension, but tend to stabilise the knee with respect to the other 5 degrees of freedom. Therefore, due to the structure of the knee, a moment acting about the knee in the frontal plane is more likely to induce abnormal movement of the knee joint than similar moment in the sagittal plane, which in turn is more likely to overload the stabilising structures (passive and dynamic) of the knee.

Hewett et al., (1996) reported values of 0.021 BW.ht for maximum normalised knee valgus moment for trained females. These values are similar to those reported in the present study of 0.0208 BW.ht for females. Hewett et al., (1996) reported values of -0.017 BW.ht for maximum normalised knee varus moment for trained females. However, in this study, throughout the landing phase used for analysis (between IC and MAX) the normalised knee moment remained in valgus for females. In untrained males, Hewett et al., (1996) reported values of 0.037 BW.ht for maximum normalised knee valgus moment and -0.049 BW.ht for maximum normalised knee varus moment. These values appear slightly higher than those measured in the present study for trained males, which are a maximum normalised knee valgus moment of 0.0116 BW.ht and a maximum normalised knee varus moment of -0.0164 BW.ht. The differences in the data reported by Hewett et al., (1996) and the present study for males are likely to be due to differences in the training status of the subjects, i.e. Hewett et al., (1996) examined untrained males whereas the present study examined trained males.

Conclusion.

The overall patterns of the normalised GRF were similar between males and females in both the sagittal and frontal planes during landing. The normalised knee extension moment was similar in pattern between males and females. Females displayed significantly smaller normalised knee extension moment at ML than males. The patterns of the normalised knee moment in the frontal plane were different between males and females. Females normalised knee moment remained in valgus throughout landing (slight increase during PP followed by decrease during AP), whereas for males, the normalised knee moment changed between valgus and varus during landing. The normalised knee varus moment exhibited by males was significantly different from the normalised knee valgus moment exhibited by females at AL and the maximum normalised knee valgus moment was significantly greater in females than males. These results indicate greater likelihood of overloading the muscles of the knee in the frontal plane during landing in females which in turn is likely to increase the strain on the on the passive support structures of the knee in maintaining joint stability. This could contribute to the reported greater incidence of non-contact ACL injury in females compared to males. Training programmes for females should incorporate exercises and practices to alter the moments exhibited by females in the frontal plane to reduce the likely strain on the passive support structures of the knee.

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Tables.

Table 1. Group mean data for ground reaction force and moments about the knee in landing manoeuvres in males and females.

Study.	**Task**	**Sagittal plane knee moment.**	**Frontal plane knee moment.**	**Ground reaction forces.**
Salci et al., (2004)	40 cm and 60 cm vertical drop landing.	F displayed significantly greater peak knee extension moment than M at 40 cm drop landing (M; 0.1±3.2 Nm/kgBM: F; 3.0±2.2 Nm/kgBM).		F exhibited significantly greater normalised peak vertical ground reaction force than M in both 40 and 60 cm drop landing (mean- M: 3.8±0.7 BW: F; 5.4±0.9 BW) .
Decker et al., (2003)	60 cm vertical drop landing.	No significant difference between M and F peak knee extension moment (M; 17.69±4.57 %BW.ht: F; 15.31±3.3 %BW.ht).		No significant difference between M and F peak normalised vertical ground reaction force (M; 3.67±0.92 BW: F; 3.39±0.89 BW).
Chappell et al., (2002)	Forward, backward and vertical stop-jump landing.	F exhibited a significantly greater knee extension moment than M in all tasks (mean estimated from graphs (+ flex, – ext) M; +0.05±0.2 BW.ht: F; -0.03±0.05 BW.ht).	F displayed a significantly greater knee valgus moment than M in all tasks (mean estimated from graphs (+ var, – val) M; +0.02±0.05 BW.ht: F; -0.02±0.06 BW.ht).	
Kernozek et al., (2005)	60 cm vertical drop landing.	No significant difference between M and F peak knee extension moment (M; 1.75±0.37 Nm/kgBM: F; 1.70±0.27 Nm/kgBM).	F displayed significantly lower peak knee varus moment than M (M; 1.61±0.72 Nm/kgBM: F; 0.93±0.69 Nm/kgBM).	F exhibited significantly greater normalised peak vertical ground reaction force than M (M: 3.51±0.63 BW: F; 4.71±0.71 BW).
Yu et al., (2006)	Stop-jump landing.	F displayed significantly greater peak knee extension moment than M (M; 0.15±0.04 BW.ht; F; 0.18±0.05 BW.ht).		F exerted significantly greater normalised peak vertical ground reaction force than M (M; 2.16±0.60 BW: F; 2.67±0.95 BW).

F = females, M = males.

Table 2. Group mean results for sagittal plane normalised GRF, knee angle and normalised knee moment (+ve = flexion moment, – ve = extension moment) at ML, AL, MAX maximum and minimum (Mean ± standard deviation).

Sagittal plane		ML (0.03 s)	AL (0.075 s)	MAX	Maximum	Minimum
Normalised GRF (BW)	Male	1.052 ± 0.170	1.772 ± 0.485	0.972 ± 0.415	1.861 ± 0.595	NA
	Female	1.160 ± 0.287	1.625 ± 0.415	0.894 ± 0.378	1.631 ± 0.427	NA
Flexion / extension (°)	Male	28.83 ± 5.30	43.60 ± 7.78	62.97 ± 11.24[1]	NA	NA
	Female	24.88 ± 4.97	46.66 ± 9.05	68.22 ± 9.49[1]	NA	NA
Normalised moment (BW.ht)	Male	-0.0433 ± 0.0353[2]	-0.1110 ± 0.0541	-0.0908 ± 0.0303	-0.1325 ± 0.0681	-0.0097 ± 0.0166
	Female	-0.0065 ± 0.0325[2]	-0.0876 ± 0.038	-0.0923 ± 0.048	-0.1100 ± 0.0309	-0.0055 ± 0.0227

[1+2] Significant difference between males and females

Table 3. Group mean results for frontal plane normalised GRF, knee angle and normalised knee moment (+ve = valgus moment, –ve = varus moment) at ML, AL, MAX maximum and minimum (Mean ± standard deviation).

Frontal plane		ML (0.03 s)	AL (0.075 s)	MAX	Maximum	Minimum
Normalised GRF (BW)	Male	1.054 ± 0.173	1.778 ± 0.486	0.977 ± 0.418	1.864 ± 0.595	NA
	Female	1.150 ± 0.302	1.601 ± 0.412	0.890 ± 0.378	1.604 ± 0.421	NA
Valgus / varus (°)	Male	-0.10 ± 7.04	-1.09 ± 7.84	-1.38 ± 9.20[1]	NA	NA
	Female	-3.00 ± 3.23	-4.54 ± 4.41	-6.79 ± 4.50[1]	NA	NA
Normalised moment (BW.ht)	Male	0.0058 ± 0.0173	-0.0085 ± 0.0212[2]	-0.0025 ± 0.0106	0.0116 ± 0.0170[3]	-0.0164 ± 0.0176
	Female	0.0192 ± 0.0199	0.0187 ± 0.0200[2]	0.0047 ± 0.0127	0.0208 ± 0.0199[3]	0.0047 ± 0.0127

[1-3] Significant difference between males and females.

Figure captions.

Figure 1. Sagittal plane normalised GRF, knee angle and normalised knee moment between IC and MAX for males and females.

Figure 2. Mean stick figures of males (a) and females (b) knee angle and normalised GRF vector in the sagittal plane at the start of muscle latency, start of active loading and maximum angle of the knee.

Figure 3. Frontal plane normalised GRF, knee angle and normalised knee moment between IC and MAX for males and females.

Figure 4. Mean stick figures of males (a) and females (b) knee angle and GRF vector in the frontal plane at the start of muscle latency, start of active loading and maximum angle of the knee.