Journal of Australian Strength & Conditioning

Knee Behaviour in Squatting. J. Aust. Strength Cond. 20(2)23-36. 2012 © ASCA

Peer Review
KNEE BEHAVIOUR IN SQUATTING.

Mark R McKean and Brendan J Burkett
Fitness Research, School of Health and Sport Science,
University of Sunshine Coast, Queensland, Australia.

ABSTRACT

An effective and often prescribed compound exercise for the lower limb is the squat movement. The purpose of this research was to determine if the leading joint hypothesis exists when squatting, that is one joint creates a dynamic foundation for motion of the entire limb. To contribute to future exercise prescription guidelines the influence of mediolateral and anteroposterior movement, the timing of the knees, and the influence of segment lengths were investigated in 29 subjects from a cross sectional back ground of sport and strength training. Subjects performed two types of squats; unloaded body weight squats and barbell squats with 50% body weight added. The 3D kinematics of the lower limb and torso were assessed with the independent variables of load, stance, phase and gender. The movement of the knees when squatting was found to support the leading joint hypothesis. The knee changed mediolateral and anteroposterior position to accommodate variations in load and stance width. The knee was also found to move past the alignment of the anteroposterior displacement of the knee, did not remain aligned with heel width, direction of the toes or anterior position of the toes. The amount of anteriorposterior displacement of the knee, with respect to the foot, varied between gender and this movement is considered anatomically appropriate and therefore should be encouraged in exercise prescription. Despite the literature, and this current research, generally supporting deep squats and the freedom for the knee to move anterior of the toes, there exists an inappropriate perception in some practical settings to restrict this movement pattern. Based on this research practitioners should allow an athletes' knees move in both mediolateral and anteroposterior direction when squatting and not remain aligned with heel width, direction of the toes, or anterior position of toes. Knee behaviour in squatting appears to be strategic and occurs in a specific order of the timing in the squat movement. Movement anterior of the toes is a normal and required part of the squat movement that should be encouraged where appropriate and when practitioners feel the clients' knees are healthy or normal.

Key Words – Squat, Synchronisation, Mediolateral, Anteroposterior, Timing.

INTRODUCTION

The squat exercise is commonly prescribed in strength training environments and for rehabilitation of the knee post-surgery and injury (5). As a closed kinetic chain movement this exercise is considered a safe lower body exercise and the ability to vary parameters such as width of stance, depth, and load enables the exercise to be matched to the requirements of the individual (4). To effectively prescribe the exercise requires an understanding of the lower limb movement patterns and relationships. From motor control research the Central Nervous System (CNS) selects muscle torques at each joint necessary for movement production which has resulted in relationships like the leading joint hypothesis (LJH) which states there is one leading joint that creates a dynamic foundation for motion of the entire limb (13). The leading joint accelerates or decelerates regardless of the subordinate joints, thus controlling the motion of the limb, whilst the other joints simply regulate muscle torque and movement for the task. In the squat movement, the LJH suggests one of the joints in the lower limb would be the leading joint thus establishing the control of the movement and the other joints would simple follow to produce the overall movement. However there is little, if any, evidence in the published literature to suggest that any of the lower extremity joints would behave in a leading joint way. To ensure appropriate prescription of this common and useful exercise the lower-limb movement patterns require more rigorous examination.

In monitoring the squat exercise a number of cues are often instigated, such as instructing the performer to maintain the mediolateral alignment of the knees with that of the feet to optimise knee stability (10). This 'knee aligned with foot position' simply directs the performer to point the knees in the same direction of the toes and results in lower limb anatomical alignment which is considered a more ideal postural position (21). Failure to achieve this suggested alignment has been previously attributed to poor hip stability or reduced core strength, but research is not in full agreement with the cause. Some findings suggest hip muscle strength does not correlate with the mediolateral movement of the knee (16), whilst others found hip external rotation torque correlated with frontal plane projection angle (23). Excessive medial movement of the knee has also been associated with increased risk of anterior cruciate ligament injury (14), and rotating the knees outward in squat lifting resulted in reduced moments and compression forces, when compared with normal squat lifting (3). These results suggest the mediolateral width of the knees, and the resultant change in knee position, occurs in some strategic manner to accommodate the effect of the typical variables of different load or width of stance adopted by the individual. Therefore the consequence of mediolateral knee movement plays an important role in the safe and effective prescription of this exercise.

In many practical environments deep squats and knees moving forward of the toes is still considered to be associated with knee injury yet the literature does not support this thinking (19,20). In the anterior-posterior plane recent research shows the knees may move up to nine centimetres forward of vertical alignment with the toes and it was suggested this forward movement of the knee may allow for improved synchronisation of the hip and knee joints (4). Again the movement pattern of the knee can be modified by restricting the forward position of the knee, resulting in compensatory movements such as an increase in forward trunk lean (12).

Segment length has been found to influence lower limb activities with negative correlations between vertical jump height and tibial length (22), and strong relationships between shank elongation and intrinsic limb dynamics (9). Segment length, however, was not a significant predictor of squat load (8). Despite these identified influences of segment length, the impact of this anthropometric measure and associated ratios on the timing and coordination in the squat movement pattern is currently unknown. Furthermore, the established distinct differences in height, and the subsequent segment lengths and ratios between men and women may also contribute to gender differences in squat movement patterns, yet little evidence exists regarding this relationship.

When quantifying the movement of the squat exercise the maximum angles of the knee (24) and hip (2) have been presented, but timing when this occurred within the phase was not defined. Using body-weight only, deeper squatting altered lower limb coordination, shifting the effort from the knee joint to the hip joint and the transition point of 65^{o} knee bend resulted in the hip and knee movements becoming more similar in behaviour (11). An extension of measuring the angle-time relationship is to quantify the rate of this change via angular velocity. Peak angular velocities have been reported previously but the relative timing of when these velocities occurred does not appear in the literature (18), preferring rather to report the angles of the other joints at the time the peak velocity occurred. The timing of these maximal velocities for both ascent and descent phases may help explain the manner in which the squat movement pattern is synchronised. These measures may identify the strategy, if any, on how these segments behave and if there is a leading joint pattern when squatting.

Therefore, the aim of this research was to examine if the leading joint hypothesis exists for the squat movement. To address this aim the timing and synchronisation of the lower limb with respect to mediolateral and anteroposterior movement and the timing of the knees when performing a squat exercise was quantified. The influence of segment lengths and ratios on the behaviour of the knees was also quantified to enable individual-specific prescription guidelines to be established.

METHODS

Approach to the Problem

Data of the lower limbs and torso was captured as subjects completed four sets of eight repetitions of the squat exercise. Subjects performed a below parallel squat which is described as a squat where the hip joint descended to a vertical point below that of the knee joint. This is shown in Figure 1. The independent variables were load, stance, phase, and gender. The dependent variables were Hip, Knee, and Shank angles, mediolateral knee width, anteroposterior knee position, Segment length, Segment ratio, and Timing. The variables for each set were two different loads; body-weight (BW), and with an external load equal to 50% of the individuals body weight (BW+) via an Olympic bar (Australian Barbell Company, Mordialloc, Victoria, Australia) and associated weight resting across the rear shoulders: and two different widths of stance; narrow stance (equal to Anterior Superior Iliac Spine – ASIS - width), and wide stance (equal to twice ASIS width) (1). The load and stance order was randomised and there was two minutes rest between sets. Data was analysed for three consecutive repetitions in the middle of each of the four sets, with subjects being blind to the actual repetitions used.

Figure 1 – Subject performing a below parallel squat with sensors attached.

Subjects

Twenty-nine healthy subjects from a cross sectional group of sub elite and strength training backgrounds (16 males and 13 females) with at least 12 months squatting experience and free of musculoskeletal injury, volunteered for the study. Informed consent was obtained and all participants informed of the experimental risks according to guidelines of the University Human Research and Ethics Committee. Anthropometric data collected for each subject included total body mass to the nearest 0.01 kg, standing height to the nearest 1 mm, and ASIS width to nearest 1 mm. Using joint centre digitisation segment length data of the thigh and shank to the nearest 1mm was measured at 120 Hz by a 3D Motion Analysis System (Motion Monitor, Version 6.50.0.1 Innovative Sports Training, Chicago, Illinois, USA) with sensors attached directly to the surface of the skin over spinous processes of T12/L1 and L5/S1, and on the anterior surface of thighs and shanks as per previous standardised placements (4). Validation of the system against standardised reference measures confirmed the variation to be less than 0.5^o and within 0.003 m.

Table 1 – Subject data and anthropometric measures presented as mean (standard deviation).

Subject	Men (n=16)	Women (n=13)
Age (years)	24.1 (5.0)	24.2 (6.3)
Weight (kg) *	84.2 (12.3)	62.1 (7.5)
ASIS width (cm) *	25.5 (1.4)	24.4 (2.1)
Height (cm) *	179.3 (6.6)	167.1 (4.7)
Thigh (cm) *	42. 2 (2.3)	39.0 (2.5)
Shank (cm) *	40.6 (2.3)	38.3 (1.8)
Torso (cm) *	82.1 (4.6)	77.8 (3.6)
Height: Torso Ratio*	2.19 (0.10)	2.15 (0.07)
Height: Leg Ratio	2.17 (0.08)	2.16 (0.06)
Torso: Leg Ratio*	1.00 (0.07)	1.01 (0.05)
Femur: Tibia Ratio *	1.04 (0.08)	1.02 (0.07)
1RM squat (kg)*	115.3 (17.6)	57.6 (13.1)

***** indicates a significance difference of $p < 0.01$ between genders

As expected, all initial segment lengths differed between genders. However, Height-Torso, Torso-Leg, and Femur-Leg ratios also showed significant gender differences. Only Height-Torso ratio was similar between genders.

Procedures

Participants warmed up and then performed a warm up set of squats. Squat technique was according to National Strength and Conditioning Association (NSCA) position guidelines on squats and monitored by a certified strength coach (6). The inside distance between the participants heels determined narrow-stance or wide-stance (1). Foot alignment in narrow-stance was toes straight ahead and wide-stance no more than 30^o away from midline. Participants performed a below parallel squat with no restriction on tempo however all subjects performed these in a slow and controlled manner. Depth determined by the vertical height of the sacrum was used to identify top and bottom of the squat, with time for descent and ascent normalised, the top of the squat 0% and bottom 100%. Hip angles were defined as the anterior angle between lines connecting knee joint centre with hip joint centre with midline of trunk. Knee angles were defined as the posterior angle between a line connecting hip joint centre with knee joint centre and ankle joint centre. The shank angle was the most anterior angle reached using a global reference system with vertical being the reference of zero degrees. Knee-width reported as the distance between knee joint centres and knee forward position reported as the distance of digitised landmarks on the patella relative to the vertical line of toes. Figure 2 shows the biomechanical angles previously discussed. Angular velocities for the hip joint, knee joint and shank angle were determined.

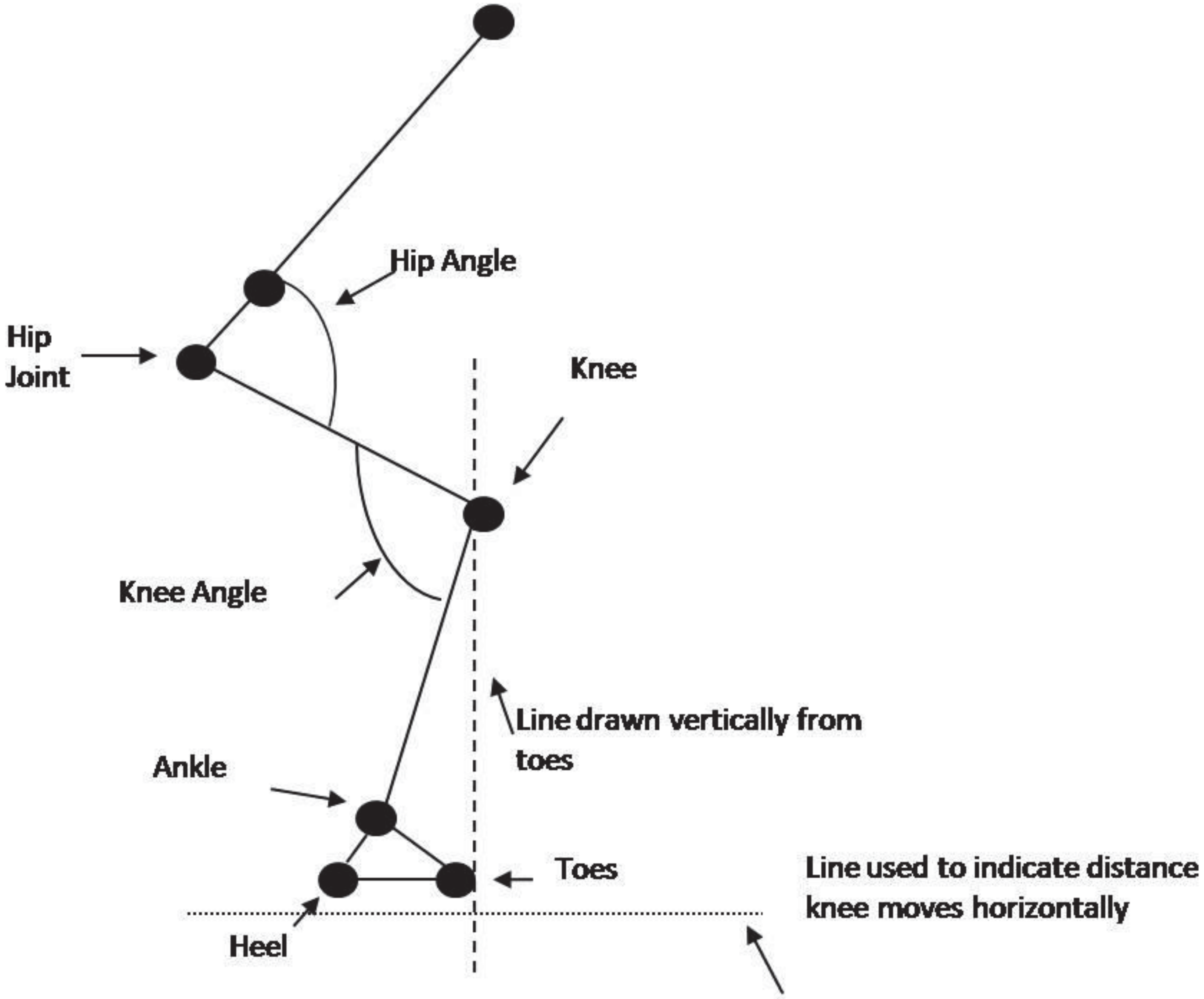

Figure 2 - Angle conventions used for analysis (4).

Statistical Analyses

The following data were analysed; (i) maximum hip angle; (ii) maximum knee angle; (iii) maximum shank angle; (iv) maximum and minimum mediolateral knee-width; (v) maximum anteroposterior knee movement, and (vi) the normalised time of when these occurred. Each of these responses were analysed separately using a repeated ANOVA for differences between load (BW or BW+), stance (narrow-stance or wide-stance), gender (male or female) and phase (ascent or decent). The results presented as mean and 95%CI. Bivariate Spearman correlations were then calculated between the different responses, segment lengths, and ratios. Values less than 0.4 represented poor correlations, 0.4 to 0.7 fair, 0.70 to 0.90 good, and greater than 0.9 represented excellent correlations. Statistical interpretation focused on the main effects and the threshold for statistical significance was set to $p < 0.05$.

RESULTS

Table 2 - The maximum hip joint flexion, knee joint flexion, and shank flexion angles and normalised time when the maximum occurred presented as mean (95% CI). Males n=16, Females n=13.

Load		**Body Weight**				**Body Weight +**			
Stance		Narrow Stance		Wide Stance		Narrow Stance		Wide Stance	
Phase		Descent	Ascent	Descent	Ascent	Descent	Ascent	Descent	Ascent
Maximum Hip Flexion Angle (degrees)	Male	77.1 (71.1,83.1)	77.1 (71.0,83.1)	72.8 (66.8,78.9)	72.7 (66.6,78.8)	73.7 (67.6,79.8)	73.7 (67.5,79.9)	70.9 (64.8,76.9)	70.7 (64.6,76.2)
	Female	77.7 (73.9,81.4)	77.7 (74.0,81.5)	76.0 (72.3,79.8)	76.3 (72.4,80.2)	76.6 (73.8,79.4)	76.6 (73.6,79.5)	73.8 (71.4,76.2)	73.7 (71.3,76.1)
Normalised Time for Maximum Hip Flexion Angle (%)	Male	98.5 (97.8,99.1)	99.0 (98.7,99.2)	98.2 (97.2,98.7)	98.6 (98.2,99.1)	98.3 (97.6,99.0)	97.6 (96.5,98.7)	98.4 (97.5,99.3)	96.9 (94.5,99.3)
	Female	98.7 (98.2,99.1)	99.0 (98.6,99.3)	98.0 (97.2,98.8)	99.1 (98.7,99.5)	98.7 (98.2,99.2)	98.9 (98.6,99.1)	99.0 (98.5,99.5)	98.9 (98.5,99.2)
Maximum Knee Flexion Angle (degrees)	Male	63.7[a] (59.8,67.6)	62.7[a] (58.6,66.8)	59.7[a] (56.7,62.7)	59.9[a] (56.8,62.9)	58.8[a] (55.3,62.2)	58.8[a] (55.3,62.4)	58.5[a] (54.3,62.6)	58.6[a] (54.5,62.8)
	Female	75.1[a] (67.8,82.4)	75.2[a] (67.9,82.4)	70.9[a] (62.8,79.0)	70.7[a] (62.8,78.6)	75.1[a] (68.7,81.5)	75.2[a] (68.5,81.8)	71.1[a] (65.5,76.7)	70.9[a] (65.3,76.6)
Normalised Time for Maximum Knee Flexion Angle (%)	Male	99.2 (98.6,99.7)	99.0 (98.7,99.2)	99.5 (99.2,99.8)	98.7 (98.1,99.3)	99.1 (98.7,99.5)	98.3 (97.6,99.1)	99.1 (98.5,99.7)	98.1 (97.7,98.5)
	Female	99.3 (98.9,99.7)	98.7 (98.3,99.0)	99.3 (98.9,99.6)	99.0 (98.7,99.3)	98.8 (98.2,99.5)	98.8 (98.3,99.2)	99.5 (99.1,99.9)	98.5 (97.9,99.0)
Maximum Shank Angle (degrees)	Male	36.3 (34.0,38.6)	34.3 (32.4,36.2)	35.7 (33.8,37.6)	36.0 (34.1,37.7)	35.4 (33.8,36.9)	36.1 (34.6,37.5)	38.2 (36.5,40.0)	38.6 (36.8,40.5)
	Female	36.7 (34.2,39.1)	34.3 (31.8,37.0)	35.3 (32.1,38.5)	35.4 (32.2,38.5)	36.8 (33.9,39.7)	36.5 (33.3,39.3)	37.4 (34.8,40.4)	38.0 (35.2,40.8)
Normalised Time for Maximum Shank Angle (%)	Male	97.8 (96.5,99.1)	94.6[b] (92.7,96.5)	96.0 (93.5,98.5)	91.3[b] (89.2,93.4)	97.5 (96.2,98.9)	91.9 (89.0,95.0)	97.6 (96.3,99.0)	88.7[b] (85.2,92.2)
	Female	97.3 (95.3,99.3)	98.0[bc] (97.2,98.7)	95.7 (92.8,98.0)	95.8[bc] (94.4,97.2)	96.3 (94.4,98.3)	95.5 (91.0,99.9)	98.6 (97.6,99.6)	95.2[b] (93.2,97.2)

[a] significant difference $P < 0.001$ for maximum knee angle between genders when comparing stance, load and phase
[b] significant difference $P < 0.001$ for shank angle normalised time between genders when comparing stance, load and phase
[c] significant difference $P < 0.001$ for shank angle normalised time for females when comparing width of stance

Initial comparisons of the joint angles and timing of the coordination of maximum angles showed gender differences across all squat variations for maximum knee angle and the normalised time for maximum shank angle in the ascent phase. The maximum knee angles difference between genders for each variation ranged from 10.8° to 16.4°. Normalised time for maximum shank angles differed significantly only in the ascent phase of each squat with a difference ranging between 3.4% and 6.5%, compared to the descent phase of less than 1.2%. Men and women achieve similar hip angles when performing below parallel squats with hip angles being within 3° for all variations, Similarly, shank angles were also less than 1.4° different between genders for all squat variations.

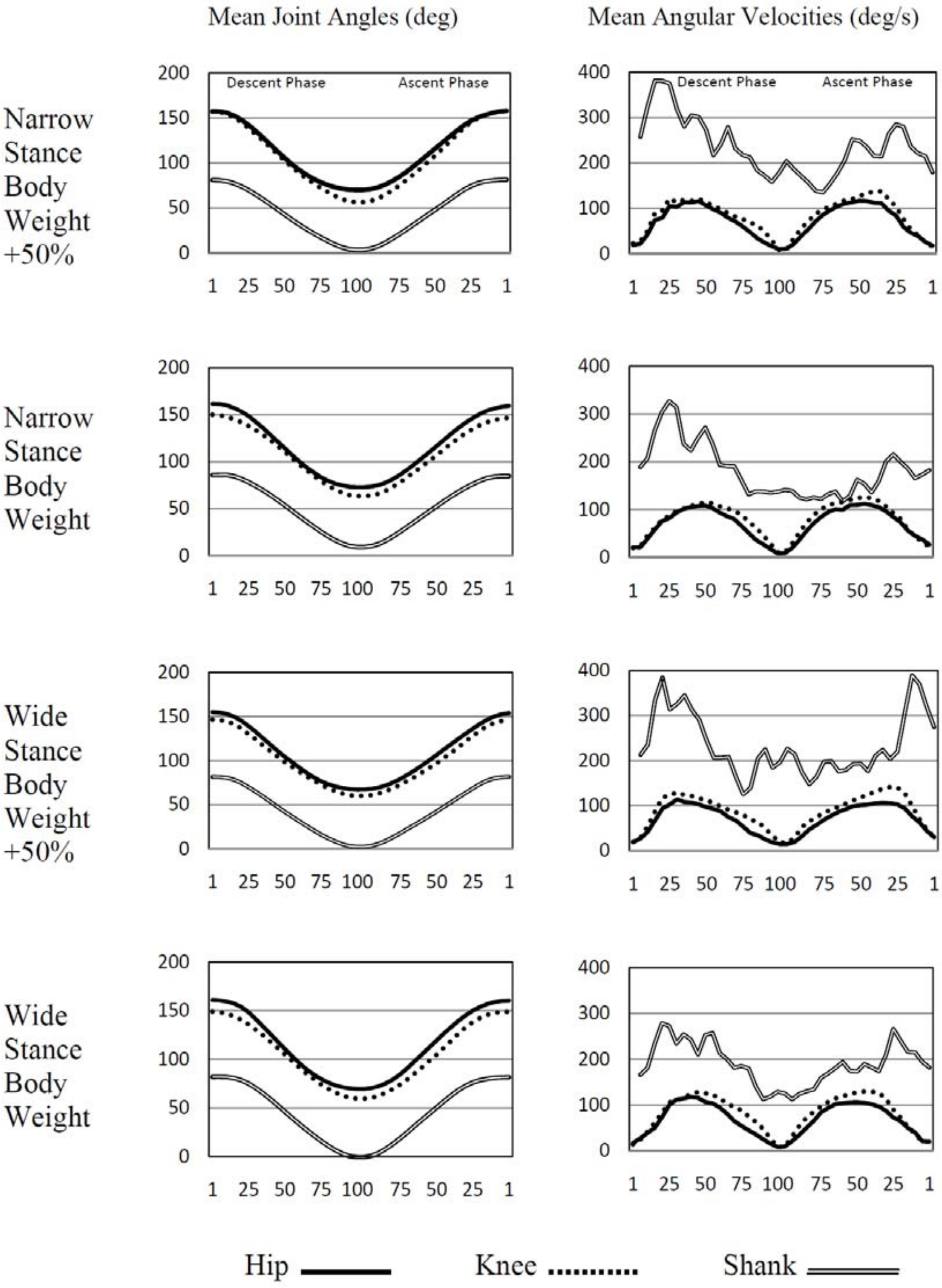

Figure 3 – Graphs of joint angles and velocities normalised over the ascent and descent phase of the squat for males.

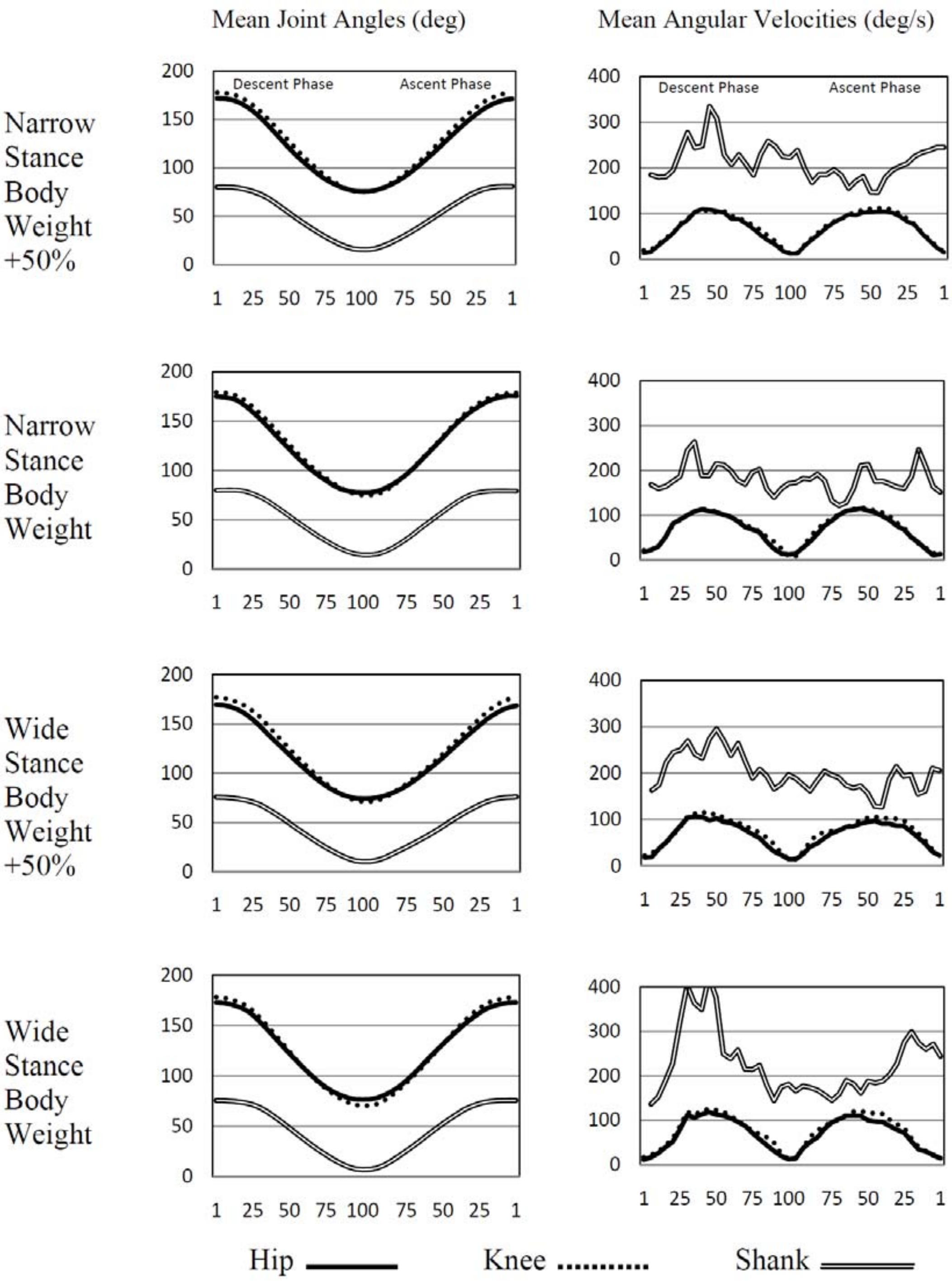

Figure 4 – Graphs of joint angles and velocities normalised over the ascent and descent phase of the squat for females.

[a] significant difference $P < 0.01$ for maximum hip velocity time in females when comparing stance in BW squats ascent phase

[b] significant difference $P < 0.01$ for maximum hip velocity time, maximum knee velocity time, and maximum shank velocity in males when comparing load in WS squats ascent phase

[c] significant difference $P < 0.01$ for maximum hip velocity time, maximum knee velocity time, and maximum shank velocity time in females when comparing load in WS squats ascent phase

[d] significant difference $P < 0.01$ for maximum knee velocity in males in maximum shank velocity and maximum shank velocity time when comparing load in NS squats ascent phase

[e] significant difference $P < 0.01$ for maximum hip velocity time in females when comparing load in WS squats descent phase

[f] significant difference $P < 0.01$ for maximum knee velocity time in males when comparing load WS squats descent phase

[g] significant difference $P < 0.01$ for maximum shank and knee velocity times in females when comparing stance in BW+50% squats for ascent phase

[h] significant difference $P < 0.01$ for maximum shank angle velocity in males when comparing load in NS squats descent phase

[i] significant difference $P < 0.01$ for maximum shank angle velocity in males when comparing stance in BW squats descent phase

[j] significant difference $P < 0.01$ for maximum shank velocity time in females when comparing stance in BW squats for both phases

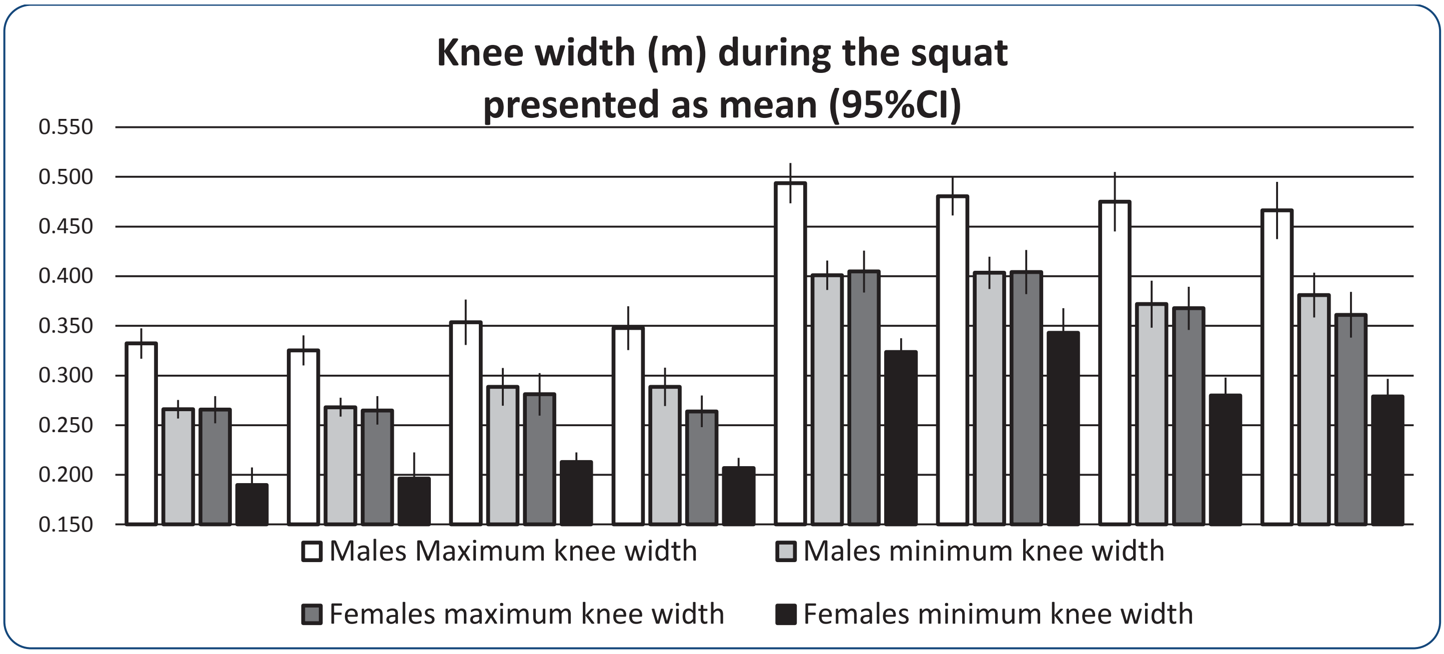

Figure 5 - Knee width (m) maximum and minimums during the squat presented as mean (95%CI).

Significant difference (p <0.01) in maximum knee width, and minimum knee width for all squats in both phases when comparing gender
Significant difference (p <0.01) for both males and females in maximum knee width for all squats in both phases when comparing width of stance
Significant difference (p <0.01) for both males and females in minimum knee width for males BW squat ascent phase, Males BW+ both phases, and females both BW and BW+ squats in both phases when comparing width of stance
Significant difference (p <0.01) for females in maximum knee width for WS squats in both phases when comparing loads
Significant difference (p <0.05) in minimum knee width for males WS descent phase, and females NS descent phase, and WS both phases when comparing loads

Knee width is described as the distance between the centrally landmarked anterior surface of the patella relative to the global system. Significant differences were found in the mediolateral maximum, and minimum knee-widths when comparing genders for all squat variations. For each squat variation, male's knees started the narrow-stance squat wider than the heels and wide-stance squats narrower than heels. Heel width was set at ASIS width yet males starting width ranged between 0.292 to 0.315 m for narrow-stance and 0.399 to 0.409 m for wide-stance squats. Females starting knee-width always started equal to or narrower than the heel width with narrow-stance range of 0.209 to 0.244 m, and wide-stance range of 0.306 to 0.363 m. Given that the wide-stance squat technique used an abducted foot position, it would be expected that knee-width would be wider than heel width as shown in males, but this was not the case for females.

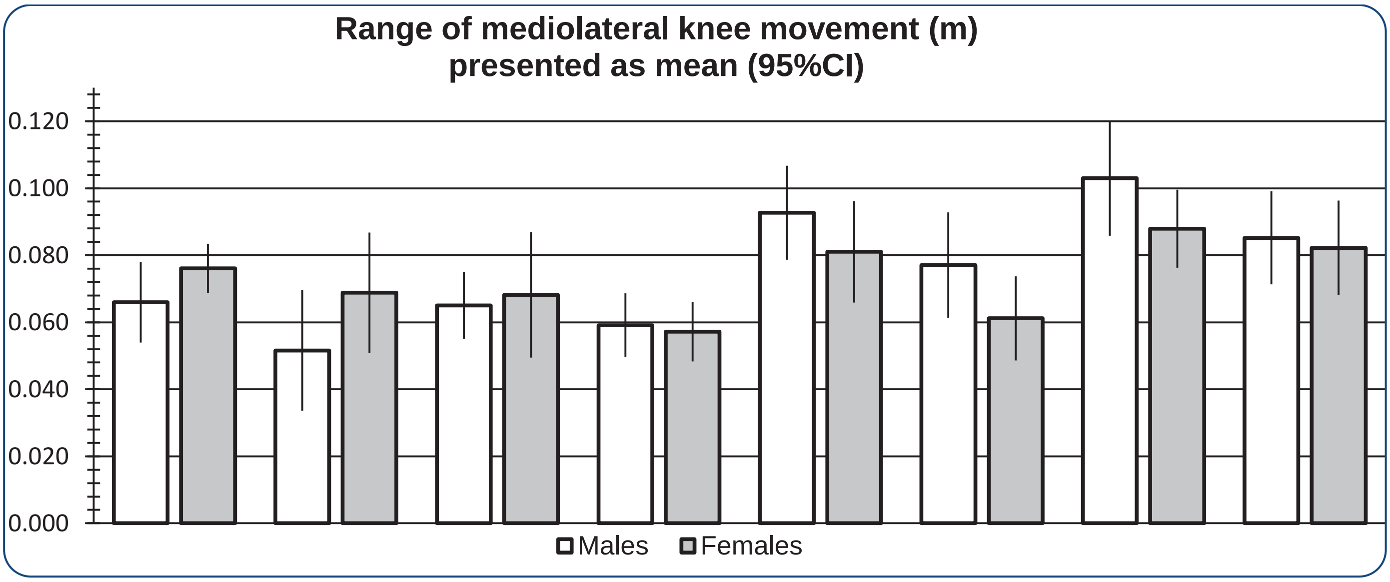

Figure 6 -Range of mediolateral knee movement presented as mean (95%CI).

Significant difference (p<0.05) in range of mediolateral knee movement for males in BW squats in ascent phase when comparing stance
Significant difference (p<0.01) in range of mediolateral knee movement for males in BW+ squats in both phases when comparing stance
Significant difference (p<0.01) in range of mediolateral knee movement for females in BW+ squats in ascent phase when comparing stance
Significant difference (p<0.05) in range of mediolateral knee movement for females in BW+ WS squats when comparing load
Significant difference (p<0.05) in range of mediolateral knee movement for females in BW WS squats when comparing phase

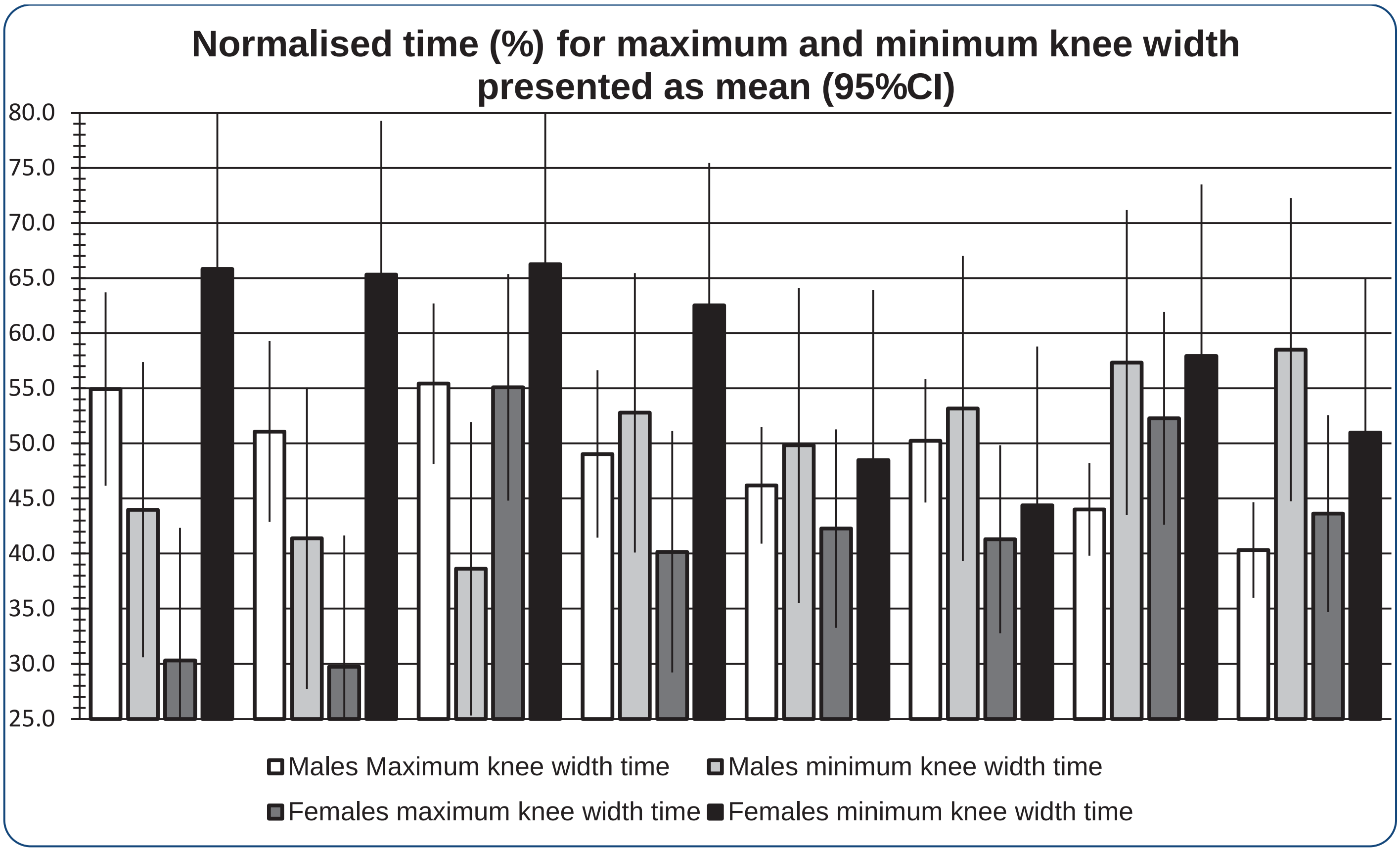

Figure 7 - Normalised time (%) for maximum and minimum knee width presented as mean (95%CI).

Significant difference (p <0.01) in maximum Knee width time for NS BW squats in both phases when comparing gender
Significant difference (p <0.05) in minimum Knee width time for NS BW squats in both phases and NS BW+ squats in the descent phase when comparing gender
Significant difference (p <0.01) in maximum Knee width time for NS BW squats in both phases when comparing gender
Significant difference (p <0.05) in maximum Knee width time for Males in BW+ squats in both phases when comparing width of stance
Significant difference (p <0.01) in maximum Knee width time for Females NS squats in descent phase, and Males WS ascent phase when comparing loads

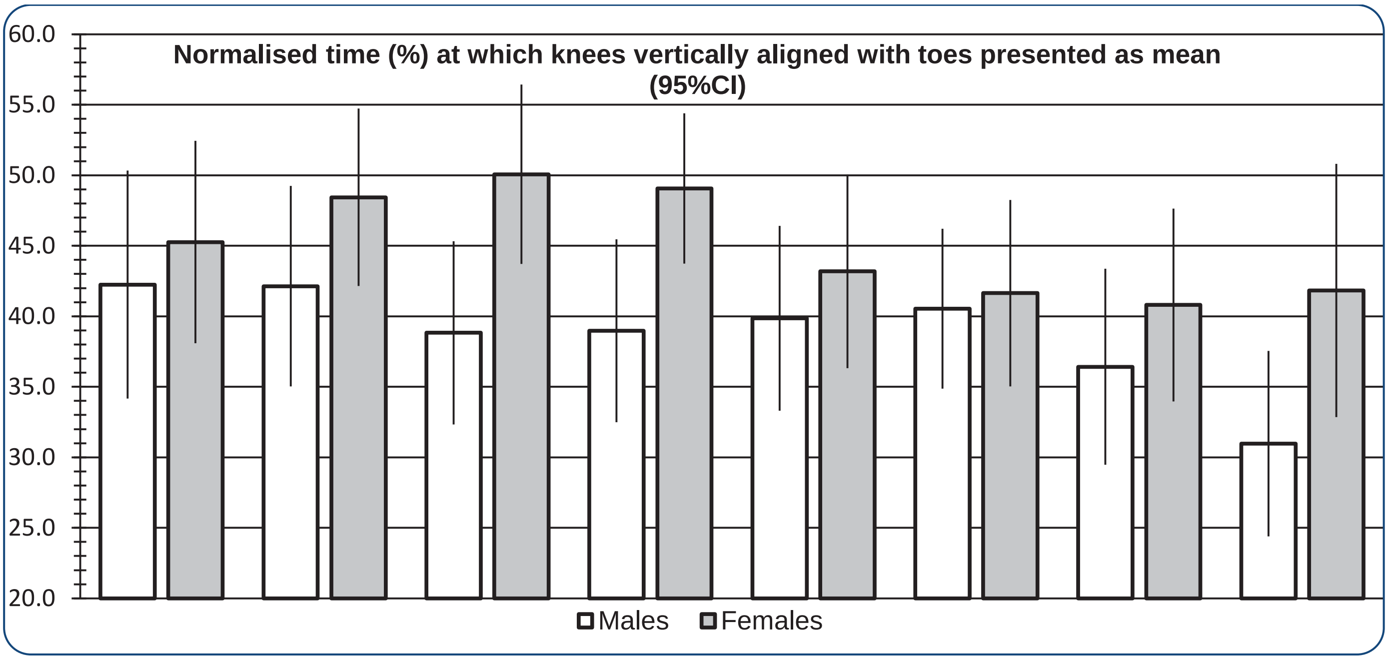

Figure 8 - Normalised time (%) at which knees were vertically aligned with toes presented as mean (95%CI).

Significant difference (p <0.05) in time for knee vertically aligned with toes for NS BW+ squats in both phases and WS BW+ squats in the ascent phase when comparing gender
Significant difference (p <0.05) in time for knee vertically aligned with toes for Males in WS squats in descent phase when comparing loads

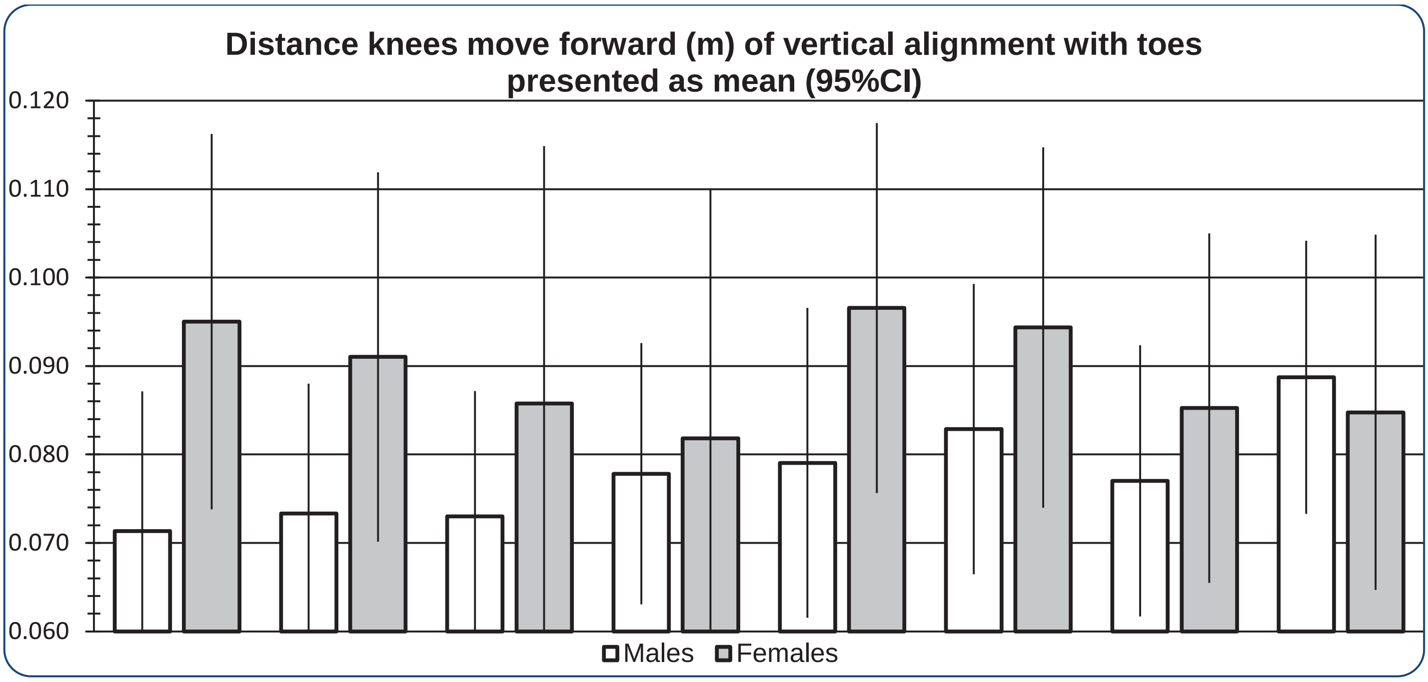

Figure 9 - Distance the knees moved forward (m) of vertical alignment with toes presented as mean (95%CI).

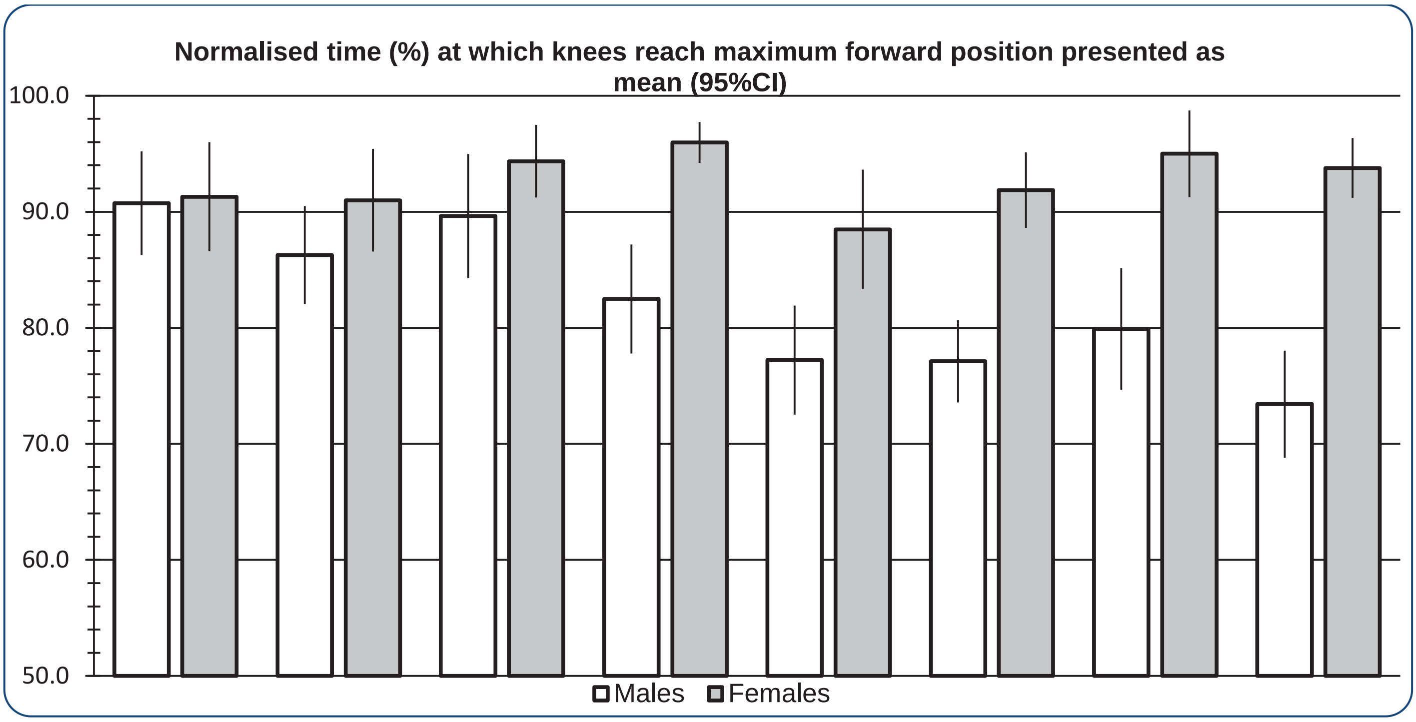

Figure 10 - Normalised time (%) at which knees reach maximum forward position presented as mean (95%CI).

Significant difference ($p < 0.01$) in time for maximum knee forward position for NS BW+ squats in ascent phase, and WSBW and WS BW+ squats in both phases when comparing gender
Significant difference ($p < 0.01$) in time for maximum forward knee position for Males in both BW and BW+ squats in both phases, when comparing width of stance
Significant difference ($p < 0.05$) in time for maximum knee forward position for Females in NS squats ascent phase when comparing loads

Table 3 - Bivariate Pearsons correlations for segment length and squat measures.

Males	Hip Angle	Knee Angle	Knee Time	Knee Forward Max	Knee Forward Time	Knee Over Toes Time	Shank Angle Max	Shank Angle Range	Knee Width Max
Height	-.406**								
Torso Length	-.424**								
Hip Time			.999**		.901**			.866**	
Knee Angle				.427**					
Knee Time					.903**			.867**	
Knee Forward Max						-.590**	-.538**		
Knee Forward Time								.837**	
Females	**Hip Angle**	**Knee Angle**	**Knee Time**	**Knee Forward Max**	**Knee Forward Time**	**Knee Over Toes Time**	**Shank Angle Max**	**Shank Angle Range**	**Knee Width Max**
ASIS Width		.415**							
Height	.436**	.593**				-.504**			
Thigh Length		.600**							
Torso Length		.451**							
Thigh Shank Ratio		.489**							
Hip Angle		.496**		.406**		-.405**			
Hip Time			.999**		.972**			.909**	
Knee Angle						-.551**	-.591**		
Knee Time					.971**			.908**	
Knee Forward Max						-.593**	-.494**		
Knee Forward Time								.846**	
Knee Over Toes Time							.592**		
Shank Angle Max									-.438**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

DISCUSSION

In order to establish the timing and synchronisation of the lower limbs when performing the squat exercise, two factors were considered; the maximum angles/position achieved at each joint/segment and the time at which these maximums occurred (Table 2). Men and women achieved similar hip angles with less than 3^{o} difference across all variations. Similarly, shank angles were also less than 1.4^{o} different between genders for all squat variations. Further, maximum hip and knee angles are achieved almost simultaneously with the deepest part of the squat - suggesting a total body coordination strategy of these movements when squatting. However, comparisons of the knee joint angles showed a significant difference ($p<0.001$) between gender across all squat variations when comparing load, stance and phase. The maximum knee angle difference between genders for each variation averaged 12.9^{o}. This suggested the knee joint may control or adjust its flexion angle during the movement in response to some other condition or strategy that differs between genders. The reported differences in height and limb length between genders from the current study do not appear to alter these results. This has not been previously reported in the literature. Female participants also appear to better synchronise the degree of flexion at the hip and knee with a mean difference of 3.0^{o} in comparison to men who differed by an average of 13.5^{o}. If synchronisation was based on achieving similar angles of the two key joints, women appear to more closely match hip and knee angles than males. This is supported by previous research which found in men, peak knee torques of the knees were achieved prior to peaks of the hip and ankle (15).

The second consideration for synchronisation was the time at which the maximum angles at each joint occurred. Regardless of load, stance, phase and gender, all maximum hip and knee angles were achieved within 2% of each other establishing almost perfect synchronisation with excellent correlations (r= .999). The graphs in Figures 1and 2 demonstrate this. Normalised time for maximum shank angles differed between genders significantly ($p<0.001$) only in the ascent phase of each squat with a difference averaging 4.7% compared with 0.8% for the descent phase suggesting a slightly different timing of the movement of the shank during the ascent phase. These results show the synchronisation of the movement of the lower limb joints differed significantly only for the maximum knees angles and shank normalised time related movements of the squat. This also suggests the maximum angles achieved at each joint and timing of the maximum angles may be two separate conditions in developing the squat movement pattern. This has also not been previously reported in the literature.

Angular velocities of the hip and knee are also shown to occur in a similar coordinated manner. From Figures 1 and 2 the graphs down the right hand side reflect similar angular velocities for both the ascent and descent phases regardless of load, stance or gender. Peak angular velocities occurred before halfway down in the descent phase (50% time) and reached just over 100 degrees per second. This peak velocity reflects the greatest change in hip and knee joint angles during the same time as shown in the graphs down the left hand side of Figures 1 and 2. The standout finding was the angular velocity of the shank angle. Instead of a smooth change in angular velocity or change in angle as presented for the other joints, the angular velocity of the shank angle is quite different and changes more frequently in shorter bursts. The authors believe this may be a counterbalance strategy where the body in motion provides continual adjustment to its position during the squat to maintain a smooth and balanced pattern. To achieve this balance some part of the moving body must be able to correct the alignment of the centre of mass to remain balanced. This rapid and frequent change in position of the shank allows the person to maintain their balance to perform the squat and maintain synchronised movement of the hip and knee throughout. This finding supports previous conclusions that the ankle joint is controlled by co-contraction of the tibialis anterior, soleus and gastrocnemius to subsequently increase stability of the ankle joint (15,7). Further research is required to determine if ankle range of movement impacts on the shank angular velocity and subsequent counteractive balance strategy suggested by the authors.

Having quantified the timing and synchronisation of the hip and knee, the next aspect of this research was to quantify the mediolateral and anteroposterior movement of the knees in a squat exercise (Figures 3-8). Statistically, there were a range of significant differences in all squat variables relating to knee-width when comparing gender (Table 3). The range of movement in knee-width for both genders was lowest for narrow-stance BW squat ascent phases with males 0.052 m and females 0.057 m, and greatest for wide-stance BW+ descent phase with males 0.103 m and females 0.088 m (Figure 4). For both genders the descent phase of the squat with the additional load (BW+) produced the greatest change in knee-width. If knee alignment was a measure of stability, narrow-stance squats produced the smallest mediolateral knee-width variability and may be considered more stable. Using mean values, male knee-widths adjusted inward on average 0.021 m whilst females adjusted inwards 0.030 m. Similarly males adjusted outwards an average 0.053 m, whilst females adjusted outwards 0.042 m. All participants changed knee-widths in both ascent and descent regardless of stance-width and load thus challenging the idea that knees should remain aligned mediolateral with feet at all times. The only data found in the literature for mediolateral knee motion involved a single limb mini squat and the literature suggests this may be due to a weakness or lack of stability (21). However no research has been conducted on normal 2 feet squat to determine if muscle weakness influences mediolateral knee movement and is a topic for future research.

For narrow-stance squats, males generally achieved the maximum mediolateral width after the minimum, this being reversed for wide-stance. For timing, both minimum and maximum mediolateral knee widths in males were achieved close together with an average difference of 10.4% compared with females of 15.9% (Figure 5). The results also show knee-width for males changed the most through the middle of each phase occurring between 40-55% for both, yet females generally achieved minimums closer to the top (29.7-55.1%) than the maximums (44.4-65.8%). Females tend to go wider early in descent and ascent follows the reverse going narrower first. This consistency in movement patterns is supported by previous research where women performed the ascent phase in the reverse order of the descent phase (17). Males only reversed the order with wide-stance, possibly due to mechanical or muscular changes about the hip and knee, or differences in limb lengths that is resolved with wide-stance. It is not clear whether mediolateral movement of the knees is a strategy for the squat or a result of these issues about the hip and knee. These changes in timing may also be due to the different contraction types for muscles in each phase. This feature has also been reported previously (7). Women adduct more during a single leg squat compared to males and this may also explain the decrease in knee-width under load causing minimum knee-widths at lower depths in the back squat movement for women (25).

The normalised time for the knees vertical alignment with the toes in the anterior direction occurred between 31.0-42.2% for males and 40.8-50.1% for females (Figure 6). Females showed a moderate negative correlation between height and the timing for knees aligned with toes in the anteroposterior direction showing shorter females reach the alignment with the toes later. Males did not achieve the same anteroposterior movement compared with females. Mean values for maximum anterior movement in males ranged 0.071-0.089 m and females ranged 0.082-0.095 m which is similar to previous research (4). Whilst the actual distance varies between males and females and individuals, movement anterior of the toes is a normal and required part of the squat movement that should be encouraged where appropriate and when practitioners feel the clients' knees are healthy or normal. The actual amount of forward movement is yet to be clearly defined and the authors suggest that practitioners use caution when judging this distance. In the current study using a cross sectional group of subjects with sub maximal loads the forward knee movement averaged 7-9 cm for males and 8-10 cm for females across all squat variations. This distance was correlated with knee angle for men suggesting as a male goes deeper in the squat and knee angle reduces, knee forward position increases. Similarly females knee forward position correlated with hip angle.

The timing of maximum anterior knee position for females ranged between 88.5-96.0% with one significant difference between timing for narrow-stance squats when comparing loads. Males produced significant differences between timing of maximum anterior knee position for all squats when comparing stance with narrow-stance (82.5-90.7%) with wide-stance (73.4-79.9%). This showed females reached maximum anterior position of the knees later than males and wide-stance allowed males to alter their movement reaching the maximum anterior position of the knees much sooner than the narrow-stance set up. The timing of the anteroposterior movement of the knees shows alignment with the toes before all participants reached halfway in the descent phase of the squat, reaching maximum anterior position well before maximum hip and knee angles (Figure 8). This early movement of the knee in the anterior direction supports the concept of the knee being the leading joint in the squat movement. The knees move in an anterior direction earlier than the other joints reaching their maximum anterior position and then remained in that position whilst the hip and knee continued to synchronise angles to perform the squat. Further, with the differences between knee angles and shank timing previously discussed, this suggests the movement of the knees in both anteroposterior and mediolateral directions are developed early in the movement to set the ideal conditions for the participant to synchronise the hip and knee in performing the squat and adjusting to suit differences in load and stance width.

The movement strategy may be further explained by considering limb length when studying the squat movement. For females, there were a number of moderate positive correlations (r= .415 to r= .600) for maximum knee angle with ASIS width, Height, Torso length, Thigh length, and Thigh: Shank Ratio (Table 3). The number of correlations for these variables suggests strong relationships exist between these segment lengths and ratio with the maximum angle at the knee achieved by females when squatting. These results show that as a female's height and segment lengths of the Torso and Thigh increase, the maximum angles of the knee joint also increase. As a deeper squat resulted in a smaller angle of the knee, this showed that taller women, or women with longer torso and thigh segments, will not achieve as deeper angles at the knee as women with smaller segment lengths. For males, Height and Torso length correlated (r= -.406, and r= -.424) in a negative manner with maximum hip angles achieved, showing taller men tended to squat with a smaller angle at the hip than their shorter counterparts. The smaller angle can be achieved by a more forward trunk angle or a deeper squat. This finding is supported in the literature which showed that there is a tendency to lean forward more using the trunk angle to adjust position for squatting and as a result reduce the hip angle to a smaller number if the knees do not travel as far forward (12).

Considering the gross movement of the squat, and comparing timing of the maximums there is a difference in the way genders perform the movement regardless of load or stance. Males tend to commence the descent phase of the squat by moving these three measures first but in different orders: knees forward of the toes, minimum and maximum knee-width. Females tend to be more structured at the beginning and less at the end of descent starting body-weight squats with maximum knee-width, knees aligned over toes, and minimum knee-width. This order is changed for body-weight plus squats with knee over toes first, maximum knee-width, and then minimum knee-width. The timing of last four measures for females are based on stance width rather than load.

PRACTICAL APPLICATIONS

The movement of the knees in squatting support the leading joint hypotheses. The knees move in both mediolateral and anteroposterior direction when squatting and do not remain aligned with heel width, direction of the toes, or anterior position of toes when using submaximal loads. This appears to be a strategic part of the movement pattern developed early in the movement to allow synchronisation between the hip and knee angles. It appears that the knee and shank alters its position in both directions to account for changes to load and stance to provide the optimal sequence of segments and joints in the squat movement. Restricting the movement of the knee during a squat will alter the movement sequence and hence place undue strain on segmental joints during the squat. The authors suggest allowing the subject to determine their own best movement sequence during the squat allowing for safety and technique issues rather than a one size fits all approach to coaching the squat. An example of this is the 'break at the hips' cue often used in coaching. The current research suggests this is not part of the normal movement pattern and coaches should consider a 'knees first' approach to developing a better squat technique.

The anteroposterior displacement of the knee shows the knee moves past the alignment of the front of the foot and this appears to also occur in a specific order of the timing in the squat movement. Whilst this measure had the greatest variation as seen in the 95%CI bars for each measure in Figure 9, the results showed that all subjects in all squat variations moved anterior of vertical knee alignment during the squat. Similarly the time at which the knees moved forward of the toes was always before the subjects reached halfway of the descent as seen in Figure 8. Maximum forward position also occurred before the deepest part of the squat and the authors suggest that this is required to allow the hips to reach the deepest aspect of the squat movement. Rather than set guidelines for forward knee movement during squatting the authors suggest viewing the forward knee movement as a precursor for synchronisation of the hip and knee angles. If the hip and knee angles are working in unison then the authors suggest that the knee forward position is reaching a desirable point to allow this synchronisation. However if viewing the subject in the sagittal plane, and the synchronisation is not clear the authors suggest reviewing the forward knee movement and coaching an adjustment until synchronisation at the hip and knee approach unison.

Finally it has been shown that males and females squat with different sequences and coordination. Males tend to squat utilising the trunk as an adjustment to correct load distribution and this shows in the correlation between hip angle and both height and torso length. The authors suggest practitioners monitor males' subjects hip and knee flexibility to ensure range of movement at these joints allows full squat depth rather than an adjustment to trunk inclination as compensation. Females tend to use the knees to adjust squat movement sequencing as seen by the significant number of correlation between knee angle and lengths. The authors suggest females would benefit from increased strength of the musculature of the knee extensors to support the knee position and also of the trunk muscles to support the trunk angle.

Finally knee width varied by an average of 8 cm across both genders and squat variations. The authors suggest this is also an important movement strategy for people to maintain the synchronisation between the knee and hip. Whilst this has not been reported previously and is not commonly accepted, the authors believe it is required and should not be discouraged if the knees move both in and out slightly during the descent and is not necessarily related to muscular weakness but may be linked with the overall movement strategy.

REFERENCES

1. Ageberg E, Bennell K, Hunt M, Simic M, Roos E, Creaby M. Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. **BMC Musculoskeletal Disorders**.11(1):265. 2010
2. Baechle T, Earle R. Essentials of Strength Training and Conditioning. Baechle T, editor. Champaign: Human Kinetics; 2000.
3. Black T, Messick B, Cipriani D. Segmental Limb Length And Vertical Jump Height. **The Journal of Strength & Conditioning Research**.24(p1):1. 2010
4. Chandler TJ, Wilson GD, Stone MH. The effect of the squat exercise on knee stability. **Medicine & Science in Sports & Exercise**.21(3):299-303. 1989 Jun
5. Chandler TJ, Stone MH. The squat exercise in athletic conditioning: A position statement and review of the literature. **National Strength & Conditioning Association Journal**.13(5):51-8. 1991
6. Dahlkvist NJ, Mayo P, Seedhom BB. Forces during squatting and rising from a deep squat. **Engineering in Medicine**.11(2):69-76. 1982
7. Dionisio VC, Almeida GL, Duarte M, Hirata RP. Kinematic, kinetic and EMG patterns during downward squatting. **Journal of Electromyography and Kinesiology**.18(1):134-43. 2008
8. Dominici N, Daprati E, Nico D, Cappellini G, Ivanenko YP, Lacquaniti F. Changes in the limb kinematics and walking-distance estimation after shank elongation: evidence for a locomotor body schema? **Journal of Neurophysiology**.101(3):1419-29. 2009 Mar
9. Dounskaia N. The internal model and the leading joint hypothesis: implications for control of multi-joint movements. **Experimental Brain Research**.166(1):1-16. 2005
10. Escamilla RF, Fleisig GS, Lowry TM, Barrentine SW, Andrews JR. A three-dimensional biomechanical analysis of the squat during varying stance widths. **Medicine & Science in Sports & Exercise**.33(6):984. 2001
11. Escamilla RF, Fleisig GS, Zheng N, Lander JE, Barrentine SW, Andrews JR, et al. Effects of technique variations on knee biomechanics during the squat and leg press. **Medicine & Science in Sports & Exercise**.33(9):1552. 2001
12. Fry AC, Smith JC, Schilling BK. Effect of knee position on hip and knee torques during the barbell squat. **The Journal of Strength and Conditioning Research**.17(4):629-33. 2003
13. Fujisawa H, Yamazaki H, Nagasaki H, editors. Role of both interaction torque and muscle torque in squatting. **XVI Congress of the International Society of Electrophysiology and Kinesiolgy**; 2006; Tonrino, Itally: ISEK; 2006.
14. Kingma I, Bosch T, Bruins L, van Dieën JH. Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading. **Ergonomics**.47(13):1365-85. 2004
15. Krosshaug T, Nakamae A, Boden B, Engebretsen L, Smith G, Slauterbeck J, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. **American Journal of Sports Medicine**.35(3):359-67. 2007
16. McKean MR, Dunn PK, J. Burkett B. The Lumbar and Sacrum Movement Pattern During the Back Squat Exercise. **The Journal of Strength & Conditioning Research**.24(10):2731-41 2010
17. McKean MR, Dunn PK, Burkett BJ. Quantifying the Movement and the Influence of Load in the Back Squat Exercise. **The Journal of Strength & Conditioning Research**.24(6):1671-9 2010
18. Panariello RA, Backus SI, Parker JW. The effect of the squat exercise on anterior-posterior knee translation in professional football players. **American Journal of Sports Medicine**.22(6):768-73. 1994 Nov-Dec
19. Scaglioni-Solano P, Song JE, Salem GJ. Lower extremity biomechanics during different squat depths. **Medicine & Science in Sports & Exercise**.37(5):S393. 2005
20. Tagesson S, Öberg B, Kvist J. Tibial translation and muscle activation during rehabilitation exercises 5 weeks after anterior cruciate ligament reconstruction. **Scandinavian Journal of Medicine & Science in Sports**.20(1):154-64. 2010
21. Thijs Y, Van Tiggelen D, Willems T, De Clercq D, Witvrouw E. Relationship between hip strength and frontal plane posture of the knee during a forward lunge. **British Journal of Sports Medicine**.41(11):723-7; discussion 7. 2007 Nov
22. Willardson JM, Bressel E. Predicting a 10 repetition maximum for the free weight parallel squat using the 45 degrees angled leg press. **Journal of Strength & Conditioning Research**.18(3):567-71. 2004 Aug
23. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. **Medicine & Science in Sports & Exercise**.38(5):945. 2006
24. Wretenberg PER, Feng YI, Arborelius U. High-and low-bar squatting techniques during weight-training. **Medicine & Science in Sports & Exercise**.28(2):218. 1996
25. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. **The American Journal of Sports Medicine**.31(3):449. 2003