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McKean, M., & Burkett, B. J. (2012). Does Segment Length Influence the Hip, Knee and Ankle Coordination During the Squat Movement? *Journal of Fitness Research*, 1(1), 23–30.

<https://research.usc.edu.au/esploro/outputs/journalArticle/Does-Segment-Length-Influence-the-Hip/99450017002621>

Document Type: Published Version

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DOES SEGMENT LENGTH INFLUENCE THE HIP, KNEE AND ANKLE COORDINATION DURING THE SQUAT MOVEMENT?

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ABSTRACT

Background: *The back squat exercise is a common and essential clinical rehabilitation exercise. As a compound movement of the lower limbs the cues to optimal movement technique are complex and difficult to identify. The aim of this study was to determine the influence of lower limb segment lengths on the biomechanics of movement when performing the back squat exercise.*

Methods: *Using 3D kinematic analysis the 28 subjects (male n = 16, female n = 12) performed four sets of eight squats. The four independent variables were: load – (i) body-weight with no external load, and (ii) body-weight plus 50% body-weight external load; and width of stance – (iii) narrow stance equal to ASIS width; and (iv) wide equal to twice ASIS width.*

Findings: *The total squat pattern was different for genders and limb length correlations showed that genders created movement patterns of the lower body in squatting, which may have resulted due to these limb length differences. Males typically lean more forward allowing their spine to create greater movement and depth during the squat. Females utilise the knees and sacrum to adjust for depth, achieve greater hip flexion, and remain upright during the squat. The frequent correlations for limb lengths with the knees in females suggest females utilise the knees as a strategy to maintain synchronisation of the squat.*

Interpretation: *Taller women typically achieved greater knee angles, and taller men achieved smaller hip angles. Males and females do create different movement strategies for the squat movement and coaches and trainers should allow for this in both teaching and cueing of the squat movement pattern.*

Keywords: technique, hip, knee, shank, gender, limb length

INTRODUCTION

Commonly referred to as a triple extension movement for the three key joints of the lower limb, the squat exercise is frequently prescribed in strength training and rehabilitative fields. In the clinical and practical setting, instructors provide technique cues relating to the performance of this exercise by referring to variables such as: the depth of squat (Colker, Swain,

& Lynch, 2002); the width of stance (M. R. McKean, Dunn, & Burkett, 2010); and the load (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; McCaw & Melrose, 1999). In the few studies where a particular technique was suggested, such as breaking from the hips to initiate the squat, little biomechanical evidence exists to show whether this was maintained or monitored while performing the squat during the study. Other variables recommended to monitor

include the accent or decent phase, as this can instigate different concentric and eccentric muscle innervations (Dionisio, Almeida, Duarte, & Hirata, 2008). Finally, within all of these technique variables differences between gender have been found in coordination strategies of squat movement patterns, further complicating the cues the clinician needs to consider when monitoring this fundamental exercise (M. R. McKean et al., 2010).

Limb length has been found to influence lower limb activities with negative correlations between vertical jump height and tibial length (Black, Messick & Cipriani, 2010), and strong relationships exist between shank elongation and intrinsic limb dynamics (Dominici et al., 2009). Segment length, however, was not a significant predictor of squat mass (Willardson & Bressel, 2004). Despite these identified influences of limb length, the impact of limb length and associated ratios on the timing and segment coordination in the squat movement pattern is currently unknown. Furthermore, the established distinct differences in height, and the subsequent limb lengths and limb length ratios between men and women may also alter squat movement patterns, yet no evidence exists to establish this relationship.

When quantifying the movement of the squat exercise the maximum angles of the knee (Dahlkvist, Mayo, & Seedhom, 1982) and hip (Wretenberg, Feng, & Arborelius, 1996) have been presented, but timing when this occurred within the phase was not defined. Using body weight only, Scaglioni-Solano et al. (2005) found deeper squatting altered lower limb coordination, shifting the effort from the knee joint to the hip joint. The transition point of 65° or greater knee bend resulted in the hip and knee movements became more similar in behaviour (Scaglioni-Solano, Song, & Salem, 2005). Other research has used sub-maximal loads to minimize fatigue (Caterisano et al., 2002), whilst loads equal to 2.5-times the subject's body weight (McCaw &

Melrose, 1999) have been reported in studies on muscle activity. In all studies reporting on hip and knee angles, height was the only anthropometric measure taken and this variable was not included in the analysis of the results. Based on the established influence of limb length on movement patterns, further knowledge is required on the influence of load and limb length when performing the squat movement.

Incorrect positioning of the hip and knees may lead to injury for those using Repetition Maximum loads, or when retraining squat movements for rehabilitation. Previous thinking has suggested knees remain aligned with toes, but that is questioned by recent research showing knees may need to deviate within certain limits to maintain synchronisation of the hip and knee joints during the squat movement (McKean & Burkett, 2012). Further, research into the changes in lumbar and sacrum angles do not provide any indication if there are changes to increased height or gender differences due to height differences (McKean, Dunn & Burkett, 2010).

In order to teach the correct pattern of movement, or retrain the preferred pattern of movement, professionals in practical clinical environments need to have an understanding of the coordinated pattern of squatting and the factors that influence this movement (Hodges & Richardson, 1999). Hence, the aim of this current study was to quantify the influence of lower-limb segment length on the movement patterns when performing the common squat exercise. This limb-segment length relationship was further stratified against the established influential variables of gender, load and width of stance.

METHODS

Twenty-eight subjects, 16 males and 12 females, who performed squats regularly in their training programs for a minimum of 12 months volunteered for the study. Subjects were informed of the experimental risks and written informed con-

sent was obtained under the guidelines approved by the University Human Research and Ethics Committee prior to any experimental testing. All subjects indicated no existing history of musculoskeletal injury.

Data from the lower limbs and torso were captured as subjects completed four sets of the squat exercise. The independent variables were load, stance, phase, and gender. The dependent variables were: hip angle, knee angle, shank angle, segment length, segment ratio, and timing. Data were collected for the movement and timing of the segments and joints throughout the full squat movement. Subjects performed four sets of eight repetitions with: two different loads – body weight with no external load, and body weight + 50% of body weight as an external load via a bar resting across the rear shoulders; and two different widths of stance – narrow stance equal to ASIS width, and wide stance equal to twice ASIS width (Escamilla et al., 2001). The order for each subject was randomised, with two minutes' rest between sets. To determine if segment length influenced the squat movement pattern, sub-maximal loads were used to reduce the possibility of non-voluntary technique changes attributed to heavy loads (Paoli, Marcolin, & Petrone, 2009). Data were analysed for three consecutive repetitions in the middle of each of the four sets, with subjects being blind to the actual repetitions used (Paoli et al., 2009).

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 (Escamilla, Fleisig, Zheng et al., 2001). The laboratory is a nationally accredited facility for athletic testing.

Real-time kinematic motion was collected at 120 Hz by a Three Dimensional Magnetic Tracking Device (Motion Monitor, Version 6.50.0.1 Innovative Sports Training, Chicago, IL). Validation of the system against standardised reference measures confirmed the variation to be less than 0.5° and within 0.0033 m. Three dimensional

magnetic tracking has been previously validated (Mills, Morrison, Lloyd, & Barrett, 2007).

Subjects warmed up prior to data collection and then with the sensors attached, initial posture captured, and a warm up set of squats performed. The inside distance between the subjects heels determined width of stance. The width of stance set by a steel measuring ruler and marks placed on the floor for each individual stance set up. Narrow-Stance (NS) equalled the pelvic width, measured from right ASIS to left ASIS and Wide-Stance (WS) was twice the pelvic width (Escamilla, Fleisig, Zheng et al., 2001).

Foot alignment showed all subjects aligned feet almost parallel in Narrow-Stance and between 20° and 30° away from midline for the Wide-Stance squat. The 50% load included an aluminium Olympic bar (Australian Barbell Company) with additional weight in the form of wooden plates. Squat depth was not limited and for safety, subjects were allowed to stop at any time and spotters were on hand should the need arise. Subjects were encouraged to perform the squat in their usual manner and all subjects squatted at least below parallel thigh. One squat cycle was complete when the subject returned to the original upright starting position. The time for both decent and ascent was normalised. Regardless of phase, the top of the squat (highest vertical displacement of the sacrum) represented 0% and the deepest (lowest vertical displacement of the sacrum) represented 100%. Hip angles reported as orthopaedic angle or the smallest anterior angle between a line connecting knee-joint centre with hip-joint centre with midline of trunk. Similarly, knee angle reported as smallest posterior angle between a line connecting hip-joint centre with knee-joint centre and ankle-joint centre. Shank angle was reported as most forward angle reached using a line perpendicular to the floor as zero, and the floor would then be 90°. Limb lengths of the shank, thigh and trunk were calculated from Three Dimensional Magnetic Tracking Device.

Statistical analyses

Responses analysed included: maximum hip angle; the time at which the maximum hip angle occurred; maximum knee angle; the time at which the maximum knee angle occurred; maximum shank angle; the time at which the maximum shank angle occurred; maximum lumbar angle; the time at which the maximum lumbar angle occurred; maximum sacrum angle; the time at which the maximum sacrum angle occurred; maximum lumbar flexion angle; the time at which the maximum lumbar flexion angle occurred. Each of these responses were analysed separately for differences between gender (men or women), phase (ascent or decent), and load (body weight or body weight +50%). The results are presented gender (men or women), load (body weight or body weight +50%), and phase (ascent or decent). Bi-variate Spearman correlations were then calculated between the different responses and segment lengths. Values < 0.4 represented poor correlation, 0.4–0.7 fair, 0.70–0.90 good, and > 0.9 excellent correlation. Statistical interpretation

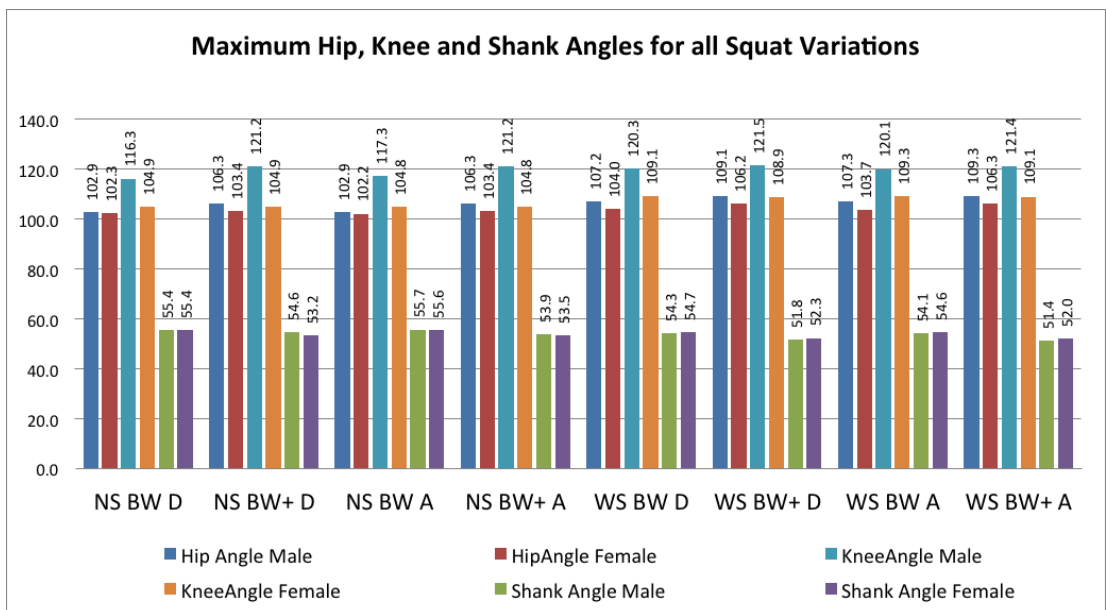
focused on the main effects and the threshold for statistical significance was set to $p < 0.01$.

RESULTS

TABLE 1: SUBJECT DATA AND ANTHROPOMETRIC MEASURES PRESENTED AS MEAN (STANDARD DEVIATION)

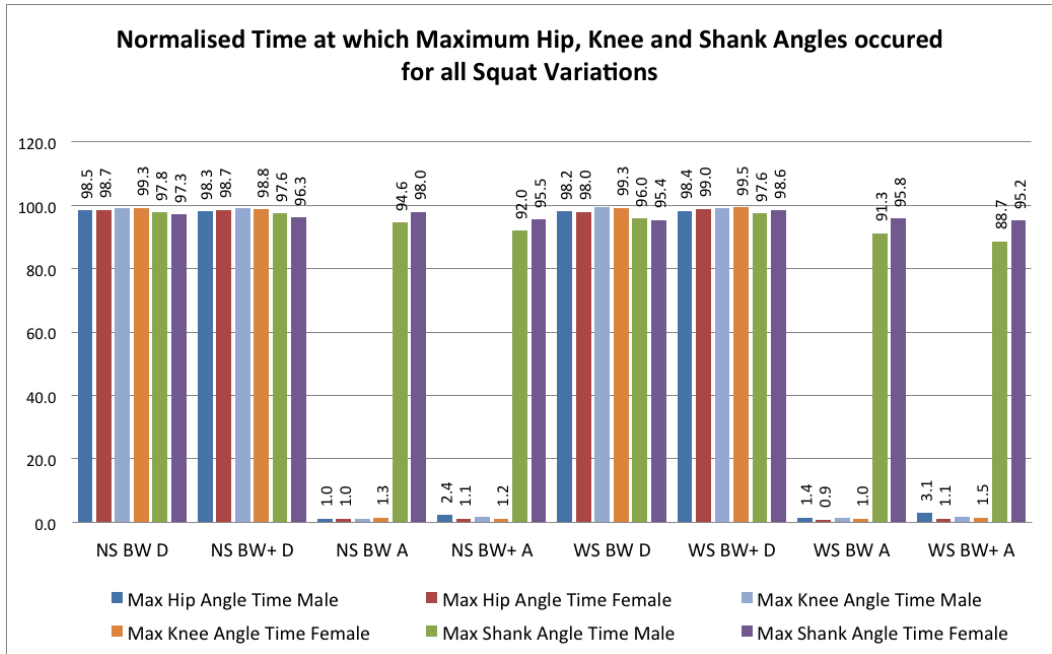
Subject	Men (n = 16)	Women (n = 12)
Age (years)	24.3 (5.1)	24.2 (6.5)
Weight (kg) *	83.2 (12.2)	62.0 (7.8)
ASIS width (cm) *	25.5 (1.3)	24.4 (2.2)
Height (cm) *	179.4 (6.8)	167.7 (5.3)
Thigh (cm) *	42.0 (2.9)	39.0 (2.6)
Shank (cm) *	40.6 (2.3)	38.3 (1.9)
Torso (cm) *	82.6 (5.0)	77.8 (3.8)
Height: Torso Ratio*	2.18 (0.10)	2.15 (0.07)
Height: Leg Ratio *	2.18 (0.08)	2.16 (0.06)
Torso: Leg Ratio	1.00 (0.08)	1.01 (0.05)
Femur: Tibia Ratio *	1.04 (0.08)	1.02 (0.08)

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



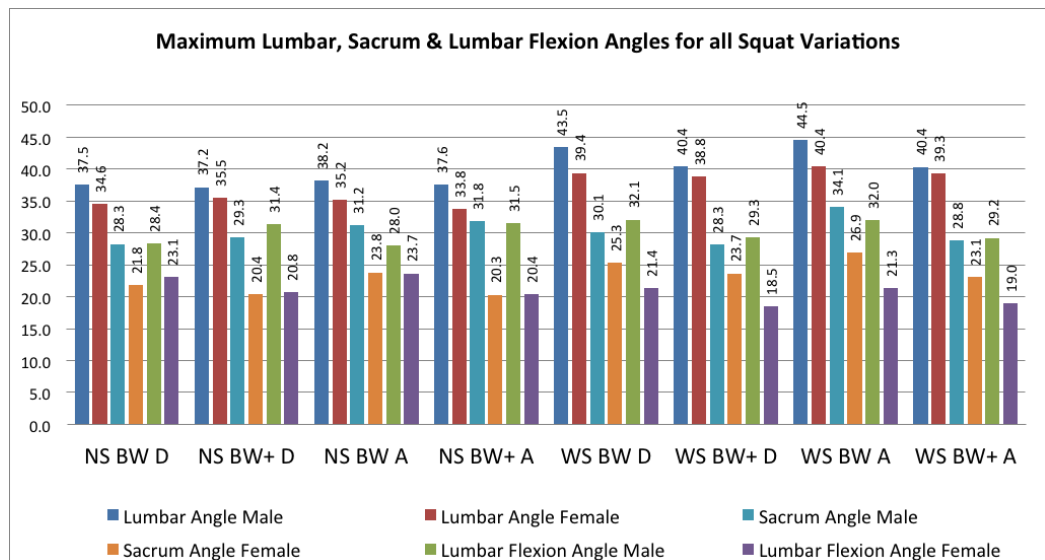
Significant difference $p < 0.01$ for maximum knee angle between genders when comparing stance, load and phase

FIGURE 1: THE MAXIMUM HIP JOINT FLEXION, KNEE JOINT FLEXION, AND SHANK FLEXION ANGLES ACHIEVED EXPRESSED IN DEGREES



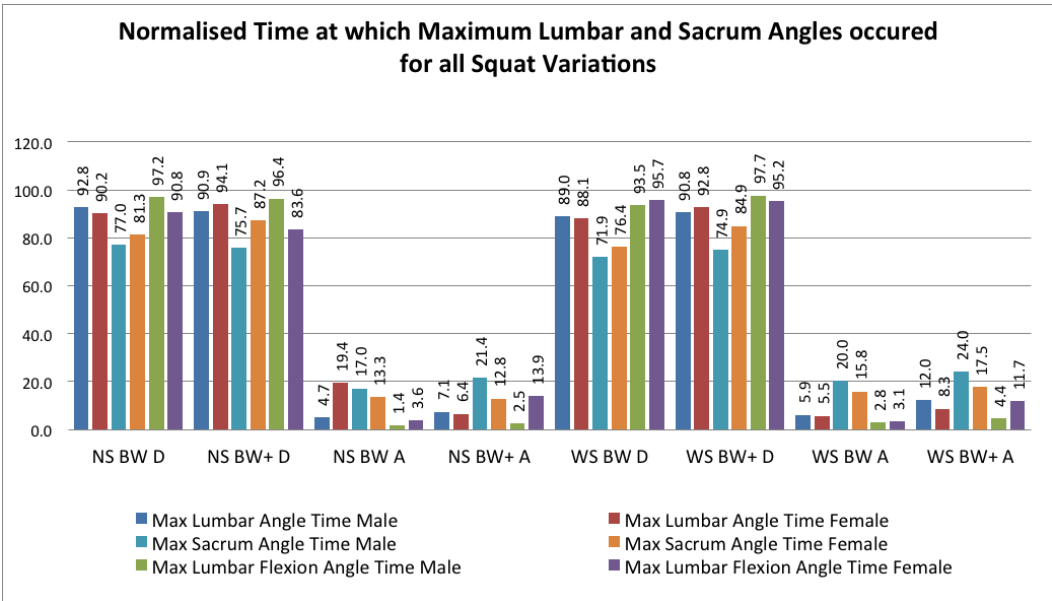
Significant difference $p < 0.05$ when comparing time at which maximum shank angle occurred for NS BW and WS BW+ during ascent phase between genders

FIGURE 2: THE NORMALISED TIME AT WHICH MAXIMUM HIP ANGLE, KNEE ANGLE AND SHANK ANGLE OCCURRED EXPRESSED AS A PERCENTAGE WITH 0% THE TOP AND 100% REPRESENTING THE DEEPEST PART OF THE SQUAT



Significant difference $p < 0.01$ for maximum sacrum angle and lumbar flexion angles between genders when comparing stance, load and phase

FIGURE 3: THE MAXIMUM LUMBAR ANGLE, SACRUM ANGLE AND LUMBAR FLEXION ANGLES ACHIEVED EXPRESSED IN DEGREES



Significant difference $p < 0.05$ when comparing time at which maximum sacrum angle and lumbar flexion angles occurred for both widths of stance and BW+ loads

FIGURE 4: THE NORMALISED TIME AT WHICH MAXIMUM LUMBAR ANGLE, SACRUM ANGLE AND LUMBAR FLEXION ANGLE OCCURRED EXPRESSED AS A PERCENTAGE WITH 0% THE TOP AND 100% REPRESENTING THE DEEPEST PART OF THE SQUAT

TABLE 2: SUMMARY OF CORRELATION FREQUENCY FOR DIFFERENT VARIABLES USING r VALUES OF 0.4 OR GREATER

Variable	Gender	ASIS width	Height	Thigh length	Shank length	Torso length
Max hip angle (degrees)	Male		-3 Descent -2 Ascent			+2 Descent +2 Ascent
	Female		+2 Descent +3 Ascent			
Max knee angle (degrees)	Male					
	Female	+2 Descent +2 Ascent	+4 Descent +4 Ascent	+4 Descent +4 Ascent		+3 Descent +3 Ascent
Max shank angle (degrees)	Male					
	Female		-2 Descent -2 Ascent			
Max lumbar angle (degrees)	Male				+3 Descent +3 Ascent	
	Female					

All correlations are two-tailed $p < 0.05$. From the variables used, it is possible for a pair to correlate no more than 8 times. If the correlation frequency occurred at least 4 times, it is reported in the table. A negative correlation shows a minus sign placed in front and positive uses a plus sign. The letter 'D' represents the descent phase and 'A' the ascent phase.

DISCUSSION

The aim of this research was to quantify the influence of limb segment length on the lower limb movement patterns, when performing the common squat exercise. Initial comparisons of the joint angles and timing of the coordination of maximum knee and shank angles shows gender differences across all variables. The reasons for these differences between genders may well be explained by the number of correlations found for the variables listed in Table 2.

For females, our results show a number of strong and moderate positive correlations for maximum knee angle with: height, torso length, thigh length, and thigh: shank ratio. The number of correlations for these four variables (26 actual from 32 possible) suggests strong relationships exist between these segment lengths and ratio with the maximum angle at the knee achieved by females when squatting. Similar relationships and number of correlations exist for maximum knee angle and maximum shank angle reached in females squat movements, with positive correlations occurring for each variation in squat technique measured.

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 deeper squat results in a smaller angle of the knee, this shows that taller women or women with longer torso and thigh segments will not achieve as deeper angles at the knee than women with reduced segment lengths. Figure 1 shows the similarities between hip angles for all squats whereas the differences in knee angles were significant across all squat variations between genders.

For males, height and torso length correlated frequently 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 was achieved by a more forward trunk angle or a deeper squat. This finding is supported by previous research showing that men tend 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 (ref).

Both men and women achieved frequent positive correlations between maximum knee and maximum hip angles showing a strong coordinated relationship between both joints when squatting. Figure 2 also shows the timing, of when the maximum angles at the hip and knee were reached for both male and female participants, was also very much the same with results showing these maxima occurred between 98.0 and 99.5% of the movement phase. As depth of the squat was measured by the lowest displacement of the sacrum, this shows that maximum hip and knee angles are achieved almost simultaneously with the deepest part of the squat suggesting a total body coordination strategy of all joints and segments to squat. Regardless of gender, and gender specific strategies for knee or hip as previously discussed the squat pattern and strategy for timing of joint movements appears to result in similar timing and coordination.

The angles and timing of the spine movements throughout squatting also show differences between genders with males achieving greater trunk lean at both lumbar and sacrum regions compared with females, which follows on from the previous comment showing males achieved smaller hip angles from the forward lean of the trunk. Lumbar flexion in males was also greater than females and the timing of this shows that females allowed their sacrum to reach its maximum later and males achieved the deeper squat by letting the lumbar flex more when the sacrum ceased moving earlier in the phase.

CONCLUSION

Taller women typically achieved greater knee angles, and taller men achieved smaller hip angles. The total squat pattern was different for genders and limb-length correlations showed that genders created movement patterns of the lower body in squatting which may have resulted due to these limb length differences.

Males typically lean more forward allowing their spine to create greater movement and depth

during the squat. Females utilise the knees and sacrum to adjust for depth, achieve greater hip flexion, and remain upright during the squat. The frequent correlations for limb lengths with the knees in females suggest females utilise the knees as a strategy to maintain synchronisation of the squat.

The implications from this research suggest that males and females do create different movement strategies for the squat movement and coaches and trainers should allow for this in both teaching and cueing of the squat movement pattern.

ACKNOWLEDGEMENT

No funding was received for this research project

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