

Research article

Relationships between Lower-Body Muscle Structure and, Lower-Body Strength, Explosiveness and Eccentric Leg Stiffness in Adolescent Athletes

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Abstract

The purpose of the present study was to determine whether any relationships were present between lower-body muscle structure and, lower-body strength, variables measured during a counter-movement jump (CMJ) and squat jump (SJ), and eccentric leg stiffness, in adolescent athletes. Thirty junior male ($n = 23$) and female ($n = 7$) surfing athletes (14.8 ± 1.7 y; 1.63 ± 0.09 m; 54.8 ± 12.1 kg) undertook lower-body muscle structure assessment with ultrasonography and performed a; CMJ, SJ and an isometric mid-thigh pull (IMTP). In addition, eccentric leg stiffness was calculated from variables of the CMJ and IMTP. Moderate to very large relationships ($r = 0.46$ - 0.73) were identified between the thickness of the vastus lateralis (VL) and lateral gastrocnemius (LG) muscles, and VL pennation angle and; peak force (PF) in the CMJ, SJ and IMTP. Additionally, moderate to large relationships ($r = 0.37$ - 0.59) were found between eccentric leg stiffness and; VL and LG thickness, VL pennation angle, and LG fascicle length, with a large relationship ($r = 0.59$) also present with IMTP PF. These results suggest that greater thickness of the VL and LG were related to improved maximal dynamic and isometric strength, likely due to increased hypertrophy of the extensor muscles. Furthermore, this increased thickness was related to greater eccentric leg stiffness, as the associated enhanced lower-body strength likely allowed for greater neuromuscular activation, and hence less compliance, during a stretch-shortening cycle.

Key words: Muscle architecture, children, associations, ultrasound

Introduction

Numerous studies have established that high levels of lower-body strength and explosiveness are key physical qualities in maximizing athletic performance (Meylan et al., 2012; Secomb et al., 2014; Sheppard et al., 2008). Furthermore, it has been highlighted how strength and explosiveness increases throughout maturity (De Ste Croix et al., 2003), and as such, it is necessary to understand how best to develop these qualities from adolescence to adulthood. Previous cross-sectional research has identified that the structural arrangement, and size of the fascicles within a muscle are associated with the expression of strength and explosiveness in adult populations (Brechue et al., 2002; Earp et al., 2010; Secomb et al., 2015b). As muscle structure has been noted as highly adaptive to training (Blazevich et al., 2007; Earp et al., 2010; Nimphius et al., 2012), it is necessary to understand the relationships between muscle structures and the ex-

pression of strength and explosiveness in adolescent athletes. Through identification of the specific muscle structures that may be related to improved strength and explosiveness, the ability to effectively prescribe training to best develop these qualities during an athlete's development may be enhanced (Secomb et al., 2015b). In addition, such data would provide the basis from which longitudinal studies can be performed, to determine whether changes in muscle structure are associated with concomitant changes in strength and explosive qualities, in adolescent athletes.

Although previous research has identified that vastus lateralis (VL) thickness and lateral gastrocnemius (LG) pennation angle are related to enhanced lower-body strength and explosiveness in adults (Brechue et al., 2002; Earp et al., 2010; Nimphius et al., 2012; Secomb et al., 2015b), to our knowledge, no research to date has investigated whether similar associations exist in adolescents. Extensive research has reported that both muscle size, and strength and explosiveness increase throughout maturation (Lloyd et al., 2011; Meylan et al., 2013; Philippaerts et al., 2006), and also that the force producing capability differences between adults and adolescents are largely due to differences in muscle size (Barrett et al., 2002; O'Brien et al., 2009; 2010). Furthermore, it has been suggested that when performing an isometric contraction, adults are able to more efficiently utilize the force-velocity and force-length relationships within a muscle, when compared to adolescents, potentially due to stiffer aponeurosis tissue (Kannas et al., 2010). As such, it may be that the associations between lower-body muscle structure and, lower-body strength and explosive qualities in adolescents, are different to those previously observed in adult populations.

It has been noted that leg stiffness may largely affect the tendons ability to store and redistribute elastic strain energy, and hence, will influence the performance of dynamic movements involving a stretch-shortening cycle (SSC) (Fukashiro et al., 2006; Fouré et al., 2010; Secomb et al., 2015b). This contention is supported by Secomb et al. (2015b), which recently identified that eccentric leg stiffness exhibited large relationships with the dynamic strength deficit (DSD) ratio, counter-movement jump (CMJ) performance, and LG pennation angle in elite adult surfing athletes. These results suggest that greater eccentric leg stiffness allowed the athletes to apply a greater magnitude of force in a dynamic movement, in relation to their maximal strength, which may be related

to increased pennation within the LG muscle (Secomb et al., 2015b). Importantly, it has been extensively demonstrated that both absolute and relative leg stiffness increase throughout maturation (Grosset et al., 2007; Lloyd et al., 2011; 2012). Additionally, Lloyd et al. (2012) reported that although older children (12 to 15 years old) exhibited greater leg stiffness than younger children (9 years old), they were not able to produce greater ground reaction forces when hopping.

Numerous studies (Earp et al., 2010; Nimphius et al., 2012; Secomb et al., 2015b) have identified that significant relationships are present between specific lower-body muscle structures, strength and explosive qualities, and the mechanical properties of the lower-body. Whilst these cross-sectional studies provide an enhanced understanding of the relationships between muscle structure and physical qualities, and a basis for longitudinal studies, it is necessary to note that these studies were performed with adult populations. As such, the application of such results to adolescents should again be made with caution, as the effects of maturation may alter any such relationships. Therefore, the purpose of this study was to investigate whether any significant relationships were present between the lower-body muscle structure, and the strength, explosive, and eccentric leg stiffness qualities of the lower-body, in adolescent athletes.

Methods

Subjects

Thirty junior competitive male ($n = 23$) and female ($n = 7$) surfing athletes (14.8 ± 1.7 y; 1.63 ± 0.09 m; 54.8 ± 12.1 kg) participated in this study. Inclusion criteria involved the following: (i) member of the surfing sports excellence squad at a local high school, (ii) currently competing at a state level or higher, and (iii) currently free of any injury or medical condition, as per a health screening questionnaire. The study and procedures were approved by University Human Ethics Committee (approval number: 10228), and conducted according to the Declaration of Helsinki. All participants and their parents/guardians were provided with information detailing the study prior to providing informed consent and were screened for medical contraindications prior to participation.

Experimental design

This study utilized a cross-sectional analysis, whereby subjects had their VL and LG muscles assessed with ultrasonography, and performed a; CMJ, squat jump (SJ), and isometric mid-thigh pull (IMTP), in a single session (Secomb et al., 2015a).

Procedures

Ultrasound: Real-time B mode ultrasonography (SSD-1000; Aloka Co., Tokyo, Japan), with a 7.5MHz linear probe was used to assess VL and LG muscle structure (Kawakami et al., 1993; 1995; Kubo et al., 2000). To measure VL muscle thickness and pennation angle, subjects were placed in a supine position, with measures taken at 50% of the distance between the greater trochan-

ter and lateral epicondyle of the femur (Earp et al., 2010; Nimphius et al., 2012; Secomb et al., 2015b). In addition, for assessment of muscle thickness and pennation angle of the LG, subjects were placed in a prone position, with measures taken at two-thirds of the distance between the lateral epicondyle of the femur and lateral malleolus (Earp et al., 2010; Nimphius et al., 2012; Secomb et al., 2015b). Two images were recorded of the VL and LG of both legs, with analysis performed as previously described in Secomb et al. (2015b). Furthermore, to calculate the fascicle length of the VL and LG, the equation reported by Fukunaga et al. (1997) (fascicle length = muscle thickness \times (\sin pennation angle)⁻¹) was utilized. For analysis, the results for both the left and right leg were combined and averaged. The Intraclass Correlation Coefficient (ICC) and Coefficient of Variation Percent (CV%) for all muscle architecture variables were considered high with ICC: 0.93-1.00 and CV%: 0.6-4.7%.

Lower-Body Strength and Explosiveness: Subjects completed the strength and explosiveness testing in the following order; CMJ, SJ, and IMTP, following a 10-minute whole-body warm-up, which consisted of squats, lunges, and dynamic mobility movements (Secomb et al., 2015a). To perform the CMJ and SJ, subjects held a wooden dowel across their backs, to eliminate any potential contribution from an arm-swing, and performed the jump on a portable force plate (400 Series Performance Force Plate; Fitness Technology, Adelaide, Australia) (Secomb et al., 2015a). Data was sampled at 600Hz, with the force plate connected to a portable laptop, utilizing an analysis software package (Ballistic Measurement System; Fitness Technology, Adelaide, Australia). Three trials of the CMJ were performed by each subject, from a self-selected depth, with the instructions to jump as high and quickly as possible (Sheppard et al., 2013). Subjects were provided with one minute of rest between each trial, and three minutes of rest prior to commencing the three trials of the SJ. The SJ trials were performed with a linear position transducer attached to the wooden dowel (PT9510; Fitness Technology, Adelaide, Australia), which was interfaced with the portable force plate (Secomb et al., In Press). The starting position of the SJ was determined whereby the top of thighs were parallel with the ground, with the subject required to hold this position for three seconds, before jumping as high as possible (Hasson et al., 2004; McGuigan et al., 2006; Sheppard et al., 2008).

Each subject's best trial for the CMJ and SJ, as determined by jump height, was used for analysis. Trials for the SJ were discarded in the event of a small amplitude countermovement of greater than 2cm, as determined by analysis of the displacement-time trace on the analysis software (Hasson et al., 2004; Sheppard et al., 2008). All jumps were analyzed for the variables of; peak force (PF), peak velocity (PV), and jump height. The ICC and CV% for these variables of the CMJ and SJ were; PF (0.98 and 3.7%, and 0.96 and 4.3%, respectively), PV (0.99 and 2.1%, and 0.78 and 4.3%, respectively), and jump height (0.88 and 4.9%, and 0.91 and 6.8%, respectively). Further, from the CMJ, a measure reflective of eccentric leg stiffness was calculated, with the equation of $F_{peak}/\Delta L$,

whereby F_{peak} is the peak ground reaction force during the eccentric phase, and ΔL is the vertical displacement of the center of mass (Farley et al., 1996; Sheppard et al., 2008; Secomb et al., 2015b). The ICC and CV% for eccentric leg stiffness was 0.96 and 5.3%. Additionally, to determine the effect of the SSC, the eccentric utilization ratio (EUR) was calculated with the following equation; EUR = CMJ jump height/SJ jump height (McGuigan et al., 2006).

Subjects performed the IMTP on the portable force plate, whilst gripping a customized pull rack, with their shoulders placed over the bar, in a position similar to that of the second pull of a power clean (Haff et al., 2005). Each subject was required to complete two trials of the IMTP, with two minutes of rest between each trial. A third trial was performed in the event that a difference in the PF between the two trials of greater than 250N was present (Kraska et al., 2009). Each subject's best trial, as determined by the trial with the highest PF, was used to determine PF and relative PF (rPF) ($N \cdot BW^{-1}$) (Secomb et al., In Press). The ICC and CV% for PF were, 0.98 and 4.2%, respectively. Furthermore, the dynamic strength deficit (DSD) ratio was calculated using the following formula; $DSD = CMJ\ PF/IMTP\ PF$, to reflect an athlete's ability to rapidly apply force during a dynamic movement, relative to their maximal force capacity (Young et al., 2014).

Statistical analyses

Mean and standard deviation ($\pm SD$) were reported for all muscle structure measures and lower-body strength and explosiveness variables (Table 1 and 2). Normality of data was assessed with a Shapiro-Wilk statistic. In the event of the assumption of normality being violated, the data was log-transformed for analysis. Pearson product-moment correlation coefficients (r) were performed on all measures to identify whether any significant relationships were present between the muscle structure measures and lower-body strength and explosiveness variables, as well as within the strength and explosiveness variables. To interpret the magnitude of relationships, the strength of the Pearson correlation coefficients were classified as 0.0-0.1 (trivial), 0.1-0.3 (small), 0.3-0.5 (moderate), 0.5-0.7 (large), 0.7-0.9 (very large), and 0.9-1.0 (near perfect) (Cohen 1988). Furthermore, the coefficient of determination (r^2) was calculated for all significant relationships to demonstrate the explained variance. Additionally, 90% confidence intervals (90%CI) were calculated for all statistically significant relationships. All statistical analyses were performed using a statistical analysis package (SPSS, Version 22.0; IBM, Chicago, USA) with statistical significance set at $p \leq 0.05$.

Results

Significant relationships were identified between the PF of the CMJ, SJ and IMTP, and thickness of both the VL and LG muscles, as well as VL pennation angle (Table 3). Additionally, eccentric leg stiffness demonstrated a large relationship with thickness of the LG ($r = 0.59, p < 0.01, 90\%CI = 0.33-0.84$), and moderate relationships with VL thickness ($r = 0.37, p = 0.04, 90\%CI = 0.08-0.66$), VL pennation angle ($r = 0.37, p = 0.04, 90\%CI = 0.08-0.66$), and LG fascicle length ($r = 0.41, p = 0.02, 90\%CI = 0.12-0.69$). Furthermore, significant relationships were present within the strength and explosiveness variables of the CMJ, SJ and IMTP, and eccentric leg stiffness (Table 4).

Table 1. Mean ($\pm SD$) recorded values for all strength and power variables of the group ($N=30$).

	Adolescent Athletes
Countermovement Jump (CMJ)	
Peak Force (N)	1134 (276)
Peak Velocity ($m \cdot s^{-1}$)	2.44 (.21)
Jump Height (m)	.41 (.06)
Eccentric Leg Stiffness ($N \cdot m$)	2821 (910)
Squat Jump (SJ)	
Peak Force (N)	1050 (254)
Peak Velocity ($m \cdot s^{-1}$)	2.54 (.27)
Jump Height (m)	.35 (.06)
Eccentric Utilization Ratio (CMJ jump height/SJ jump height)	1.16 (.14)
Isometric Mid-Thigh Pull (IMTP)	
Peak Force (N)	1520 (412)
Relative Force ($N \cdot BW^{-1}$)	2.8 (.4)
Dynamic Strength Deficit Ratio (CMJ peak force/IMTP peak force)	.76 (.10)

Discussion

The purpose of this study was to determine whether any significant relationships were present between specific lower-body muscle structures, and lower-body strength and explosive qualities, and eccentric leg stiffness, in adolescents. The results of this study identified that the thickness of both the VL and LG muscles, as well as VL pennation angle were significantly related to PF in the CMJ, SJ, and IMTP. Additionally, eccentric leg stiffness demonstrated significant relationships with thickness of the VL and LG muscles, and VL pennation angle, as well as, CMJ, SJ and IMTP PF. Further, IMTP PF was significantly related to both CMJ and SJ jump height. However, the relationship of the calculated eccentric leg stiffness with PF during the CMJ should be evaluated with caution

Table 2. Mean ($\pm SD$) recorded values for all muscle structure measures of the group ($N=30$).

	VL			LG		
	Muscle Thickness (cm)	Pennation Angle ($^{\circ}$)	Fascicle Length (cm)	Muscle Thickness (cm)	Pennation Angle ($^{\circ}$)	Fascicle Length (cm)
Left Leg	2.06 (.39)	17.21 (3.21)	7.08 (1.30)	1.39 (.19)	14.58 (3.22)	5.71 (1.24)
Right Leg	2.09 (.38)	17.33 (3.36)	7.21 (1.61)	1.38 (.27)	14.76 (3.03)	5.59 (1.44)
Combined	2.08 (.37)	17.27 (2.62)	7.14 (1.23)	1.38 (.20)	14.67 (2.76)	5.65 (1.12)

Table 3. Correlation coefficients (*r*) (90% Confidence Intervals; CI), explained variance and interpreted strength of relationships between peak force (rPF) for the countermovement jump (CMJ), squat jump (SJ) and isometric mid-thigh pull (IMTP), and; thickness of the lateral gastrocnemius (LG) and vastus lateralis (VL), and pennation angle VL.

Variable One	Variable Two	<i>r</i>	Explained Variance (%)	<i>p</i>	90%CI Lower	90%CI Upper	Strength of Relationship
CMJ PF	LG Thickness	.66	44	<.01	.43	.90	Large
	VL Thickness	.67	45	<.01	.44	.91	Large
	VL Pennation	.54	29	<.01	.27	.80	Large
SJ PF	LG Thickness	.71	50	<.01	.48	.92	Very Large
	VL Thickness	.73	53	<.01	.50	.93	Very Large
	VL Pennation	.58	37	<.01	.31	.83	Large
IMTP PF	LG Thickness	.54	29	<.01	.27	.80	Large
	VL Thickness	.67	45	<.01	.43	.90	Large
	VL Pennation	.46	21	<.01	.18	.74	Moderate

Table 4. Correlation coefficients (*r*) between countermovement jump (CMJ), squat jump (SJ) and isometric mid-thigh pull (IMTP) peak force (PF), peak velocity (PV), jump height, and relative peak force (rPF), and eccentric leg stiffness, eccentric utilization ratio (EUR), and dynamic strength deficit (DSD).

	CMJ				SJ			IMTP		rPF
	PF	PV	Height	Stiffness	PF	PV	Height	EUR	PF	
CMJ	PF	-								
	PV	.45*	-							
	Height	.43*	.88**	-						
	Stiffness	.81**	.13	.20	-					
SJ	PF	.95**	.36*	.36	.82**	-				
	PV	.32	.75**	.70**	.13	.30	-			
	Height	.38*	.77**	.78**	.17	.29	.74**	-		
	EUR	-.04	-.18	-.08	.04	-.04	-.35	-.67**	-	
IMTP	PF	.87**	.56**	.48**	.58**	.80**	.35	.48**	-.18	-
	rPF	.39*	.54**	.46*	.14	.21	.27	.40*	-.01	.69**
	DSD	-.02	-.35*	-.20	.27	.04	-.17	-.32	.33	-.49**

* $p < 0.05$, ** $p < 0.01$

since the correlation is between PF and a variable created by a ratio including that PF which may inflate the relationship.

The results of this study add to previous literature through the identification of the specific muscle structures that are related to lower-body strength, explosiveness, and eccentric leg stiffness qualities in adolescent athletes. In the present study, greater thickness in the VL and LG muscles, and VL pennation angle were related to an increased expression of dynamic (CMJ and SJ) and isometric strength (IMTP) in the adolescent athletes. This is similar to research in adult athletes that has also identified significant relationships between the thickness of the VL and performance in the CMJ, SJ, IMTP, and one-repetition maximum squat (Brechue et al., 2002; Nimphius et al., 2012; Secomb et al., 2015b). These results provide further support to the contention that increased thickness and pennation of the lower-body extensors, which is likely due to greater hypertrophy, allows for a greater production of maximal force (Kawakami et al., 1993; Zatsiorsky et al., 2006; Secomb et al., 2015b). However, to our knowledge these results are novel within an adolescent population. As previously suggested this is likely due to a greater number of subunits with the muscle, which increases cross-bridging of the muscle fibers, and hence, enhanced force producing capabilities (Kawakami et al., 2000; Zatsiorsky et al., 2006; Secomb et al., 2015b). To determine whether greater hypertrophy within an adolescent athlete's lower-body extensors results in concomitant increases in the ability to produce

force, longitudinal training studies should be performed investigating these factors.

Interestingly, the present cohort also demonstrated significant relationships between LG thickness and CMJ, SJ and IMTP PF. Conversely, no significant relationships were identified between these variables with the adult population investigated previously (Secomb et al., 2015b). However, the present results are in agreement with Earp et al. (2010), which reported significant relationships between LG thickness and peak power in the CMJ ($\beta = 0.48$, $p = 0.01$), SJ ($\beta = 0.43$, $p = 0.03$), and drop depth jump ($\beta = 0.40$, $p = 0.05$). Whilst this may be merely the result of increased subject numbers, compared to that of Secomb et al. (2015b), there could be other possible explanations.

As LG muscle thickness was related to enhanced lower-body strength and explosiveness in the present adolescent cohort, but not in those adult subjects in Secomb et al. (2015b), it may be that the adolescent athletes gained greater contribution from the ankle plantarflexors relative to adult athletes. This contention is supported by Prilutsky and Zatsiorsky (1994) which reported that the amount of work a muscle can perform is proportional to its volume. Furthermore, during jumping the body will inherently attempt to perform the majority of work around the hip joint (proximal extensor muscles), as the moment of inertia is lower, and hence, requires less energy cost. However, if there is insufficient volume in the proximal extensor muscles to perform the majority of the work, then the distal extensor muscles will be recruit-

ed to a greater magnitude. As a result, it may be that the present adolescent athletes had to rely on greater contribution from the lateral gastrocnemius muscles, due to lower muscle thickness in the vastus lateralis compared to adult athletes.

In the present cohort, IMTP PF was significantly related to CMJ and SJ jump height, which is in agreement with previous research in adult athletes (Secomb et al., In Press). This highlights that maximal strength also underpins explosiveness in adolescents, as well as adults. Furthermore, in this study the thickness of the VL and LG muscles, and pennation of the VL, were significantly related to eccentric leg stiffness. Additionally, eccentric leg stiffness exhibited large, and very large strength relationships to IMTP PF, and SJ PF, respectively. Together, these results suggest that in the present adolescent subjects, those with greater hypertrophy of the lower-body extensors exhibited an associated increase in eccentric leg stiffness, and lower-body isometric and dynamic strength. These results are in agreement with Dasteridis et al. (2012), which noted that in a group of adolescent athletes, both neurophysiological and hypertrophy factors underpinned increases in isometric quadriceps strength. It has previously been identified that the athletes with greater lower-body strength are able to employ a faster eccentric velocity during a SSC (Cormie et al., 2010), which may help explain the results of this present study. As a faster eccentric velocity increases neuromuscular activation during a SSC due to an increased stretch reflex, which in turn increases the muscle-tendon units' inherent stiffness (Komi et al., 1997; Cormie et al., 2011), it appears likely that the adolescent athletes with greater lower-body strength, and VL and LG thickness, are able to demonstrate increased eccentric leg stiffness due to enhanced neuromuscular activation.

Conclusion

In the present study, the adolescent athletes with the greater VL and LG thickness demonstrated an enhanced expression of dynamic and isometric force producing capabilities. This is likely the result of greater hypertrophy within the extensor muscles of the lower-body, which improves muscle cross-bridging (Zatsiorsky et al., 2006). Additionally, a moderate relationship was present between IMTP PF and jump height in the CMJ and SJ, which suggests that lower-body strength underpins the expression of lower-body explosiveness in these adolescent athletes. Furthermore, eccentric leg stiffness was associated with VL and LG thickness, and IMTP PF. These relationships likely exist as greater lower-body strength allows for increased eccentric velocity during a SSC, which increases neuromuscular activation (Cormie et al., 2010), and hence, improves the inherent stiffness of the muscle-tendon unit. Future research should investigate whether training-specific adaptations in lower-body muscle structure are associated with a concomitant change in strength, explosiveness and eccentric leg stiffness qualities.

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References

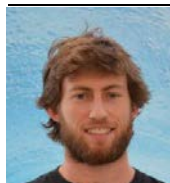
- Barrett, U. and Harrison, D. (2002) Comparing muscle function of children and adults: Effects of scaling for muscle size. *Pediatric Exercise Science* **14**(4), 369-376.
- Blazevich, A.J., Cannavan, D., Coleman, D.R. and Horne, S. (2007) Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *Journal of Applied Physiology* **103**(5), 1565-1575.
- Brechue, W.F. and Abe, T. (2002) The role of FFM accumulation and skeletal muscle architecture in powerlifting performance. *European Journal of Applied Physiology* **86**(4), 327-336.
- Cohen, J. (1988) *The concepts of power analysis*. 2nd ed. Hillsdale, New Jersey.
- Cormie, P., McGuigan, M.R. and Newton, R.U. (2010) Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and Science in Sports and Exercise* **42**(9), 1731-1744.
- Cormie, P., McGuigan, M.R. and Newton, R.U. (2011) Developing maximal neuromuscular power. *Sports Medicine* **41**(1), 17-38.
- Dasteridis, G., Piliandis, T., Mantzouranis, N. and Aggelousis, N. (2012) The effects of athletics training on isometric strength and EMG activity in adolescent athletes. *Biology of Exercise* **8**(1), 37-46.
- De Ste Croix, M.B., Deighan, M.A. and Armstrong, N. (2003) Assessment and interpretation of isokinetic muscle strength during growth and maturation. *Sports Medicine* **33**(10), 727-743.
- Earp, J.E., Kraemer, W.J., Newton, R.U., Comstock, B.A., Fragala, M.S., Dunn-Lewis, C., Solomon-Hill, G., Penwell, Z.R., Powell, M.D. and Volek, J.S. (2010) Lower-body muscle structure and its role in jump performance during squat, countermovement, and depth drop jumps. *The Journal of Strength and Conditioning Research* **24**(3), 722-729.
- Farley, C.T. and Gonzalez, O. (1996) Leg stiffness and stride frequency in human running. *Journal of Biomechanics* **29**(2), 181-186.
- Fouré, A., Nordez, A. and Cornu, C. (2010) Plyometric training effects on Achilles tendon stiffness and dissipative properties. *Journal of Applied Physiology* **109**(3), 849-854.
- Fukashiro, S., Hay, D.C. and Nagano, A. (2006) Biomechanical behavior of muscle-tendon complex during dynamic human movements. *Journal of Applied Biomechanics* **22**(2), 131-147.
- Fukunaga, T., Ichinose, Y., Ito, M., Kawakami, Y. and Fukashiro, S. (1997) Determination of fascicle length and pennation in a contracting human muscle in vivo. *Journal of Applied Physiology* **82**(1), 354-358.
- Grosset, J.-F., Mora, I., Lambertz, D. and Pérot, C. (2007) Changes in stretch reflexes and muscle stiffness with age in prepubescent children. *Journal of Applied Physiology* **102**(6), 2352-2360.
- Haff, G.G., Carlock, J.M., Hartman, M.J., Kilgore, J.L., Kawamori, N., Jackson, J.R., Morris, R.T., Sands, W.A. and Stone, M.H. (2005) Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *The Journal of Strength and Conditioning Research* **19**(4), 741-748.
- Hasson, C.J., Dugan, E.L., Doyle, T.L., Humphries, B. and Newton, R.U. (2004) Neuromechanical strategies employed to increase jump height during the initiation of the squat jump. *Journal of Electromyography and Kinesiology* **14**(4), 515-521.
- Kannas, T., Kellis, E., Arampatzi, F. and Saez Saez de Villarreal, E. (2010) Medial gastrocnemius architectural properties during isometric contractions in boys and men. *Pediatric Exercise Science* **22**(1), 152-164.
- Kawakami, Y., Abe, T. and Fukunaga, T. (1993) Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *Journal of Applied Physiology* **74**, 2740-2740.
- Kawakami, Y., Abe, T., Kuno, S.-Y. and Fukunaga, T. (1995) Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology and Occupational Physiology* **72**(1-2), 37-43.
- Kawakami, Y., Ichinose, Y., Kubo, K., Ito, M., Imai, M. and Fukunaga, T. (2000) Architecture of contracting human muscles and its

- functional significance. *Journal of Applied Biomechanics* **16**(1), 88-97.
- Komi, P.V. and Gollhofer, A. (1997) Stretch reflexes can have an important role in force enhancement during SSC exercise. *Journal of Applied Biomechanics* **13**, 451-460.
- Kraska, J.M., Ramsey, M.W., Haff, G.G., Fethke, N., Sands, W.A., Stone, M.E. and Stone, M.H. (2009) Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology and Performance* **4**(4), 461-473.
- Kubo, K., Kanehisa, H., Takeshita, D., Kawakami, Y., Fukashiro, S. and Fukunaga, T. (2000) In vivo dynamics of human medial gastrocnemius muscle-tendon complex during stretch-shortening cycle exercise. *Acta Physiologica Scandinavica* **170**(2), 127-135.
- Lloyd, R.S., Oliver, J.L., Hughes, M.G. and Williams, C.A. (2011) The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys. *The Journal of Strength and Conditioning Research* **25**(7), 1889-1897.
- Lloyd, R.S., Oliver, J.L., Hughes, M.G. and Williams, C.A. (2012) Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *Journal of Electromyography and Kinesiology* **22**(1), 37-43.
- McGuigan, M.R., Doyle, T.L., Newton, M., Edwards, D.J., Nimphius, S. and Newton, R.U. (2006) Eccentric utilization ratio: effect of sport and phase of training. *The Journal of Strength and Conditioning Research* **20**(4), 992-995.
- Meylan, C.M., Cronin, J., Hopkins, W.G. and Oliver, J. (2013) Adjustment of measures of strength and power in youth male athletes differing in body mass and maturation. *Pediatric Exercise Science* **26**(1), 41-48.
- Meylan, C.M., Cronin, J.B., Oliver, J.L., Hughes, M.G. and McMaster, D. (2012) The reliability of jump kinematics and kinetics in children of different maturity status. *Journal of Strength and Conditioning Research* **26**(4), 1015-1026.
- Nimphius, S., McGuigan, M.R. and Newton, R.U. (2012) Changes in muscle architecture and performance during a competitive season in female softball players. *Journal of Strength and Conditioning Research* **26**(10), 2655-2666.
- O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A. and Maganaris, C.N. (2009) Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children. *Experimental Physiology* **94**(6), 731-738.
- O'Brien, T.D., Reeves, N.D., Baltzopoulos, V., Jones, D.A. and Maganaris, C.N. (2010) In vivo measurements of muscle specific tension in adults and children. *Experimental Physiology* **95**(1), 202-210.
- Philippaerts R.M., Vaeyens, R., Janssens, M., Van Renterghem, B., Matthys, D., Craen, R., Bourgeois, J., Vrijens, J., Beunen, G. and Malina, R.M. (2006) The relationship between peak height velocity and physical performance in youth soccer players. *Journal of Sports Sciences* **24**(3), 221-230.
- Prilutsky B.I. and Zatsiorsky, V.M. (1994) Tendon action of two-joint muscles: transfer of mechanical energy between joints during jumping, landing, and running. *Journal of Biomechanics* **27**(1), 25-34.
- Secomb, J.L., Farley, O.R., Lundgren, L., Tran, T.T., King, A., Nimphius, S. and Sheppard, J.M. (2015a) Associations between the performance of scoring manoeuvres and lower-body strength and power in elite surfers. *International Journal of Sports Science and Coaching*. (In Press).
- Secomb, J.L., Lundgren, L., Farley, O.R., Tran, T.T., Nimphius, S. and Sheppard, J.M. (2015b) Relationships between lower-body muscles structure and lower-body strength, power and muscle-tendon complex stiffness. *Journal of Strength and Conditioning Research* **29**(8), 2221-2228.
- Secomb, J.L., Tran, T.T., Lundgren, L., Farley, O.R. and Sheppard, J.M. (2014) Single-leg squat progressions. *Strength and Conditioning Journal* **36**(5), 68-71.
- Sheppard, J.M., Cronin, J.B., Gabbett, T.J., McGuigan, M.R., Etzebarria, N. and Newton, R.U. (2008) Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *Journal of Strength and Conditioning Research* **22**(3), 758-765.
- Sheppard, J.M. and Doyle, T.L. (2008) Increasing compliance to instructions in the squat jump. *The Journal of Strength and Conditioning Research* **22**(2), 648-651.
- Sheppard J.M., McGuigan, M.R. and Newton, R.U. (2008) The effects of depth-jumping on vertical jump performance of elite volleyball players: an examination of the transfer of increased stretch-load tolerance to spike jump performance. *Journal of Australian Strength and Conditioning* **16**(4), 3-10.
- Sheppard, J.M., Nimphius, S., Haff, G.G., Tran, T.T., Spiteri, T., Brooks, H., Slater, G. and Newton, R.U. (2013) Development of a comprehensive performance-testing protocol for competitive surfers. *International Journal of Sports Physiology and Performance* **8**(5), 490-495.
- Young, K., Haff, G., Newton, R., Gabbett, T. and Sheppard, J. (2014) Assessment and monitoring of ballistic and maximal upper body strength qualities in athletes. *International Journal of Sports Physiology and Performance*.
- Zatsiorsky, V.M. and Kraemer, W.J. (2006) *Science and practice of strength training*. 2nd ed. Human Kinetics, Champaign.

Key points

- Greater thickness of the VL and LG muscles were significantly related to an enhanced ability to express higher levels of isometric and dynamic strength, and explosiveness in adolescent athletes.
- Isometric strength underpinned performance in the CMJ and SJ in these athletes.
- Greater lower-body isometric strength was significantly related to eccentric leg stiffness, which is potentially the result of greater neuromuscular activation in the muscle-tendon unit.

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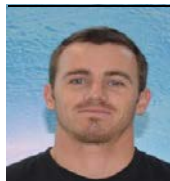
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