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Relationship between jumping abilities and skeletal muscle architecture of lower limbs in humans: Systematic review and meta-analysis

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ABSTRACT

The aim of this study was to examine the influence of skeletal muscle architecture (SMA) features measured by 2-D ultrasonography on jumping performance in humans.

A systematic review and meta-analysis was conducted, registry number: CRD42016043602.

The scientific literature was systematically searched in eight databases, last run on March 14th, 2017. Cross-sectional studies focused on the association between SMA features and vertical jumping performance were selected. A random-effects model was used to analyze the influence of lower-limb SMA and maximal jump height. A total of 11 studies were included in the qualitative synthesis and 6 studies were selected for meta-analysis. 250 correlations were reviewed across studies. The vast majority were either not statistically significant (185; 74%), weak or very weak (169; 68%) for different jump modalities; counter-movement jump (CMJ), squat jump (SJ), and drop jump. There was insufficient data to perform meta-analysis on muscles other than vastus lateralis for CMJ and SJ. The meta-analyses did not yield any significant association between vastus lateralis SMA and SJ height. Only a significant overall association was shown between vastus lateralis thickness and CMJ height (summary-r = 0.28; 95% confidence interval (CI) = −0.05 to 0.48; p = .059) for a 90% CI level. No differences were found between summary-r coefficients for SMA parameters and jump height during both jumps (CMJ: $\chi^2 = 2.43$; df = 2; p = .30; SJ: $\chi^2 = 0.45$; df = 2; p = .80) with a low heterogeneity ratio. Current evidence does not suggest a great influence of lower-limb SMA on vertical jumping performance in humans.

1. Introduction

Skeletal muscle architecture (SMA) can be defined as the arrangement of muscle fascicles within a muscle relative to the line of action of the tendon (Lieber & Fridén, 2000). The most common method of measuring SMA is through B-mode ultrasonography, which has proven to be a reliable method (reported intra-class correlation coefficients higher than 0.7) when large limb muscles are imaged in a relaxed state and the joint remains in static position (Kwah, Pinto, Diong, & Herbert, 2013).

A single image from a portable ultrasound can measure SMA, including muscle fascicle length, pennation angle, and muscle thickness. Fascicle length is usually defined as the distance between the intersection composed of the fascicle and the superficial and deep aponeuroses (Blazevich, 2006; Kawakami, Abe, Kanehisa, & Fukunaga, 2006; Narici, Franchi, & Maganaris, 2016). Pennation angle is calculated as the angle between the muscle fascicle and deep aponeurosis whereas muscle thickness is the vertical line from the superficial aponeurosis to deep aponeurosis (Blazevich, 2006; Kawakami et al., 2006).

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SMA influences the ability of muscle to produce force as well as the velocity at which force can be produced. In terms of muscle architectural design, the greater muscles thickness and pennation angles, the more amount of skeletal muscle contractile tissue in parallel and therefore, more force can be generated (Abe, Loenneke, & Thiebaud, 2015; Blazevich, 2006). Longer fascicles are thought to possess a higher peak shortening velocity due to having a greater number of sarcomeres in series (Blazevich, 2006; Lieber & Fridén, 2000; Narici et al., 2016).

The architectural features of a muscle have been considered as the best predictors of force generation, strongly affecting function (Lieber & Fridén, 2000). However, although reviews of scientific literature have highlighted several mechanical determinants of jumping performance (Alexander, 1995; James, Navas, & Herrel, 2007), yet the influence of SMA on jumping performance in humans remains poorly understood and, to our knowledge, no systematic review has been previously conducted on this issue.

Therefore, the objective of this systematic review and meta-analysis is to evaluate the relationships between SMA features of lower limbs measured by B-mode ultrasonography and jumping performance.

2. Methods

2.1. Protocol and registration

This systematic review and meta-analysis was designed according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) and registered on the International Prospective Register of Systematic Reviews (PROSPERO) in the Centre for Reviews and Dissemination (University of York, United Kingdom): CRD42016043602.

Confirmation that a review of this nature had not been published or was in progress was obtained prior to commencement through a search in the NIHR PROSPERO and the Cochrane Library databases.

2.2. Inclusion and exclusion criteria

Articles were identified by two independent reviewers for inclusion and in-depth examination. The inclusion criteria were (*i*) original cross-sectional studies focused on relating SMA features with respect to vertical jump biomechanical analysis [counter-movement jump (CMJ), squat jump (SJ) and drop jump (DJ)], (*ii*) studies performed on sports practitioners and healthy participants, and (*iii*) studies using static B-model ultrasonography measures. Discrepancies in article inclusion between reviewers were resolved by consensus. The exclusion criteria disallowed studies developed with animals.

2.3. Study selection and data extraction

Electronic databases were searched by two reviewers (JJRJ and JDRC), using a systematic detailed and reproducible search strategy to identify published evidence. Databases were accessed via the Catholic University of Murcia, Spain, and included in PubMed/Medline, Web of Science Core-Collection, Science Direct, CINAHL, Sport Discus, Academic Search Complete, with the last search being run on March 14th, 2017.

The search procedure was performed using the following terms: "muscle architecture", "pennation angle", "pinnation angle", "fibre length", "fiber length", "fascicle length", "cross sectional area", "muscle thickness", jump*. Search terms were combined by Boolean logic (AND, OR) and had to be included in the title, abstract or keywords of studies:

#1: "muscle architecture" OR "pennation angle" OR "pinnation angle" OR "fibre length" OR "fiber length" OR "fascicle length" OR "cross sectional area" OR "muscle thickness"
#2: jump*
#3: #1 AND #2.

In order to reduce publication bias, the search was performed with no restrictions on date or language. The reference lists of included studies were scanned and the grey literature was also searched (i.e. dissertations) (Hopewell, Clarke, & Mallett, 2005). The authors of published papers were also contacted directly if crucial data were not reported in the original papers.

From the initial search, the titles and abstracts were reviewed to exclude any clearly irrelevant studies. The full texts of the remaining studies were then retrieved and read in full by two authors (JJRJ and JDRC) independently to determine whether the studies met the inclusion criteria. Any disagreement was resolved by consensus with the third author (JRD).

Using an *ad hoc* data collection form, data extraction from the included studies was performed by one reviewer (JJRJ) and cross-checked by a second (JDRC).

The Pearson product-moment correlation coefficients (usually noted as *r*) reported by the authors of included studies were interpreted, in absolute value, as very weak (<0.20), weak (0.20–0.40:), moderate (0.40–0.60:), strong (0.60–0.80:) and very strong (0.8–1) (Feinstein, 2001).

2.4. Risk of bias assessment

As obtaining and replicating US images is sensitive to the methodology used, the degree of protocol description was evaluated by two blinded and independent reviewers (JJRJ, JRD) with an *ad hoc* ten-item checklist: 1) Description of participant position, 2) Description of explored anatomical region with precision, 3) US slice direction, 4) Type and characteristics of transducer, 5) Use and application of interposition material, 6) Description of US device, 7) Detailed explorations parameters, 8) Variables measured, 9) Reliability of measurements.

2.5. Statistical analysis

Since a meta-analysis involving few studies with high heterogeneity may be considered methodologically incorrect, because there is a problem estimating the between-studies variance (Borenstein, Hedges, Higgins, & Rothstein, 2010; Ioannidis, Patsopoulos, & Rothstein, 2008), a meta-analysis was performed between SMA of lower limbs and maximal jump height if at least four sample groups showed low to moderate heterogeneity ratio (I^2 0 to <75%). Moreover, because the biomechanical contribution of each muscle differs during jumping as well as between jump modalities, the meta-analyses were classified by type of jump and muscle selected.

Effect sizes were calculated through the Pearson product-moment correlation coefficient (r). Since the variance depends strongly on the correlation, the r-coefficient was converted to the Fisher's z scale.

The transformation from the sample correlation r to Fisher's z is given by

$$z = 0.5 \ln\left(\frac{1+r}{1-r}\right) \tag{1}$$

and the standard error is

$$SE_z = \sqrt{\frac{1}{n-3}}, \tag{2}$$

where n is the sample size.

The Fisher's z statistic is assumed for normally distributed data and so, the 95% confidence interval was computed as

$$z \pm 1.96(SE_z), \tag{3}$$

Finally, an inverse transformation was performed to report the results in the scale of the r-coefficient

$$r = \frac{e^{2Z} - 1}{e^{2Z} + 1} \tag{4}$$

The random-effects model (REM) was chosen due to the heterogeneity of the included studies which could affect the results (Borenstein et al., 2010). The meta-analysis was performed with the DerSimonian (DerSimonian & Laird, 1986) and Laird's method, where the weighting of sample size was introduced into the model as the inverse of variance. The overall effect was analyzed with a Student-t test (significance level $p < .10$).

The heterogeneity was checked by Q statistic that followed a central chi-squared distribution with k-1 degrees of freedom (significance level at $p < .10$) (Higgins, Thompson, Deeks, & Altman, 2003) but also by T^2 (95% CI) to estimate between-studies variance and by I^2 (95% CI) to estimate the ratio of true heterogeneity to total variation in the observed effects (Huedo-Medina, Sánchez-Meca, Marín-Martínez, & Botella, 2006). I^2 statistic may be interpreted (with caution) <25%, 50% and >75% as low, moderate and large heterogeneity, respectively (Higgins et al., 2003).

Egger's regression test (Egger, Davey Smith, Schneider, & Minder, 1997) was used to evaluate the publication bias in the meta-analysis. Publication bias was assumed when the intercept of the regression line was significantly different from zero (significance level at $p < .10$).

Finally, prediction intervals were created to address the distribution of true effect sizes. The forest plot was performed for each SMA parameter and type of jump. The statistical analysis was performed with the Review Manager v.5.3 software (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 204) and with an *ad hoc* template spreadsheet in Microsoft Excel 2010®.

3. Results

3.1. Characteristics of included studies

The flowchart is shown in Fig. 1. The literature search resulted in 736 studies with one study added after reviewing grey literature. A total of 175 studies were screened and 13 studies were full-text assessed for eligibility from which two studies were excluded because they had no relationship between muscle architectural features and vertical jumping variables. No additional studies among the reference lists of the included articles were found. A total of 11 studies analyzing the relationship between SMA and vertical jumping during CMJ, SJ, and DJ were included in the qualitative synthesis of this systematic review. Six studies were included in the quantitative synthesis of this meta-analysis.

All studies included on this systematic review were cross-sectional observational studies published between 2005 and 2017, being four of these published in 2015 (Dobbs, Gill, Smart, & McGuigan, 2015; Methenitis et al., 2016; Secomb, Lundgren et al., 2015; Secomb, Nimphius et al., 2015).

3.2. Participants

The total sample was composed of 310 participants (239 males, 71 females). Samples sizes ranged between 17 (Dobbs et al., 2015) and 62 (Alegre, Lara, Elvira, & Aguado, 2009) participants. The age of the subjects ranged between 14.8 (Secomb et al., 2015) and 68.2 (Selva Raj, Bird, & Shield, 2017) years old.

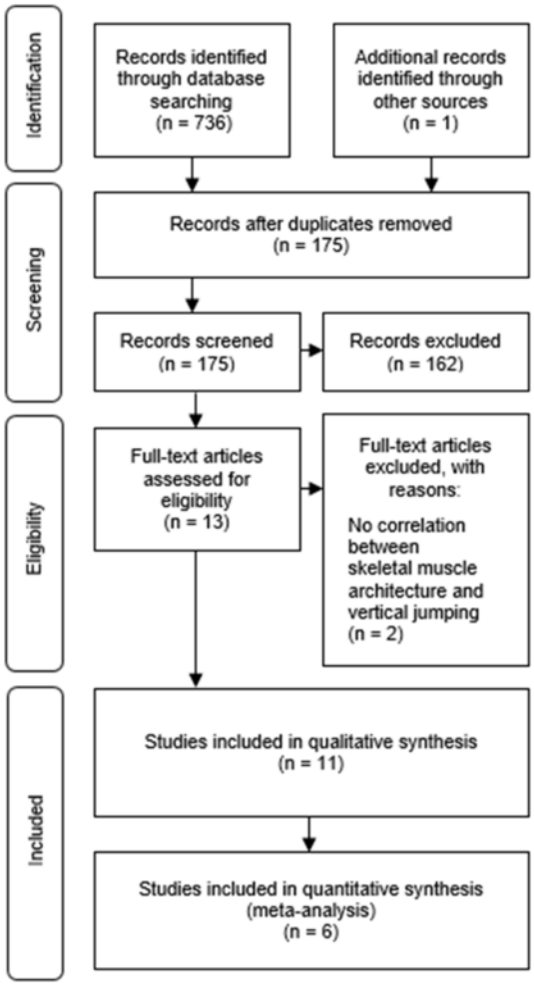

Fig. 1. Flow diagram of the literature search.

Five studies (Dobbs et al., 2015; Earp et al., 2011; Methenitis et al., 2016; Secomb, Lundgren et al., 2015; Secomb, Nimphius et al., 2015) recruited systematically trained samples. Four studies employed physically active participants (Alegre, Aznar, Delgado, Jimenez, & Aguado, 2005; Mangine et al., 2014) or heterogeneous physical conditioning (sedentary, physically active and highly trained) (Alegre et al., 2009; Rodríguez-Juan, Jiménez-Reyes, Ríos-Díaz, & Samozino, 2015) and one study included healthy community-dwelling older adults (Selva Raj et al., 2017).

3.3. Outcomes of included studies

3.3.1. Unadjusted results

A total of 250 correlations were reviewed across the selected studies. The results were focused on SMA of vastus lateralis (VL), biceps femoris, rectus femoris, gastrocnemius lateralis and medialis which were correlated to center of mass force, velocity, power, maximal jump height, mechanical impulse and rate of force development during 0–10, 10–30 and 30–50 ms periods.

Upper leg muscles showed 171 correlations whereas 81 correlations were counted for lower leg muscles. Regardless of the outcome assessed, VL muscle architecture was the most analyzed across studies showing a total of 135 correlations (78, 45, and 12 correlations for CMJ, SJ, and DJ, respectively). Rectus femoris was only correlated to CMJ variables (26 correlations) and biceps femoris was correlated five times for CMJ and five times for SJ variables. Gastrocnemius lateralis was correlated 32 times for CMJ, 27 times for SJ, and 19 times for DJ whereas gastrocnemius medialis was only correlated three times for CMJ variables. The absolute and relative frequencies are shown below as a function of the findings.

The great majority of correlations between SMA parameters and jumping ability measures were either non-significant (185; 74%), weak or very weak (169; 68%) during the different jump modalities: CMJ, SJ, and DJ (Fig. 2). Significant correlations were mostly moderate to very strong (63; 25.2%) while only two (0.8%) significant correlations were described as weak.

Most of the significant correlations were positive (60/65; 92.3%) while five significant correlations were negative. Regarding upper leg muscles, VL muscle thickness, physiological cross-sectional area, pennation angle, and fascicle length showed positive correlation to center of mass force, velocity, power, rate of force development (0–10 ms) and maximal jump height. However, some negative associations were counted for VL fascicle length and pennation angle with center of mass velocity, power, and maximal jump height for CMJ and SJ. Rectus femoris muscle thickness, pennation angle, and fascicle length showed positive correlations to power for CMJ and SJ whereas a negative association was showed for rectus femoris pennation angle and center of mass velocity for CMJ. No significant correlations were counted for biceps femoris SMA.

Concerning SMA of lower leg muscles, gastrocnemius lateralis muscle thickness, pennation angle, and fascicle length showed positive significant correlations to center of mass force, velocity, power, maximal jump height and rate of force development (0–10, 10–30, 30–50 ms) for CMJ, SJ, or DJ whereas gastrocnemius medialis muscle thickness and fascicle length showed two positive significant correlations to maximal jump height for CMJ.

3.3.2. Meta-analysis

There was insufficient data to perform meta-analysis on muscles other than VL for CMJ and SJ. Therefore, a total of 6 datasets (n = 183 participants; Vastus lateralis [min-max]: thickness = 1.8–4.6 cm; fascicle length = 6.4–12.2 cm; pennation angle = 12.9–18.6 degrees; Maximal jump height [min-max]: CMJ = 0.25–0.57 m; SJ = 0.29–0.48 m) provided unadjusted data on the association between VL muscle architecture and maximal jump height during SJ and CMJ in healthy participants with different physical condition (Alegre et al., 2005; Alegre et al., 2009; Methenitis et al., 2016; Rodríguez-Juan et al., 2015; Secomb, Lundgren et al., 2015; Selva Raj et al., 2017).

Six meta-analyses were performed by type of jump (CMJ and SJ) and by SMA parameter (pennation angle, thickness and fascicle length) of VL. Figs. 3 and 4 show a complete statistical description with the forest plot.

For the relationships between SMA parameters of VL and jump height in CMJ, a non-significant association was found for pennation angle (Fig. 3a) (summary-r = 0.23; 95% CI = −0.05 to 0.48; p = 0.100) and for fascicle length (Fig. 3c) (summary-r = −0.10; 95% CI = −0.48 to 0.31; p = 0.63) but a significant association was found for muscle thickness (Fig. 3b) (summary-r = 0.28; 95% CI = −0.05 to 0.48; p = .059).

For the SMA associations with jump height in SJ, the associations were not significant for either pennation angle (Fig. 4a) (summary-r = −0.02; 95% CI = −0.29 to 0.25; p = .874), muscle thickness (Fig. 4b) (summary-r = 0.12; 95% CI = −0.26 to 0.48; p = .536) or fascicle length (Fig. 4c) (summary -r = −0.05; 95% CI = −0.45 to 0.36; p = .630).

The heterogeneity significance tests (χ^2 Q) showed non-significant results only for the studies that evaluated the association between pennation angles and jump high both in CMJ and SJ. T^2 statistics showed that the variance between studies was lower for pennation angle vs. CMJ jump height and higher for fascicle length vs. CMJ jump height.

Finally, the I^2 *index,* that could be interpreted as the ratio of true heterogeneity to total variation in observed correlations, showed a low heterogeneity for pennation angle in SJ (I^2 = 0%; 95% CI = 0–69%) and in CMJ (I^2 = 40%; 95% CI = 0–76%).

The Egger's regression-method showed that the intercept coefficient was 0.11 (95% CI = −0.16 to 0.38; p = .415) so it can be concluded that there was no publication bias.

After analyzing the differences of the summary-r coefficients (black diamonds) for thickness, pennation angle and fascicle length, no differences were found in CMJ (χ^2 = 2.43; df = 2; p = .30) with a low heterogeneity ratio (I^2 = 17.7%) or in the SJ meta-analy-

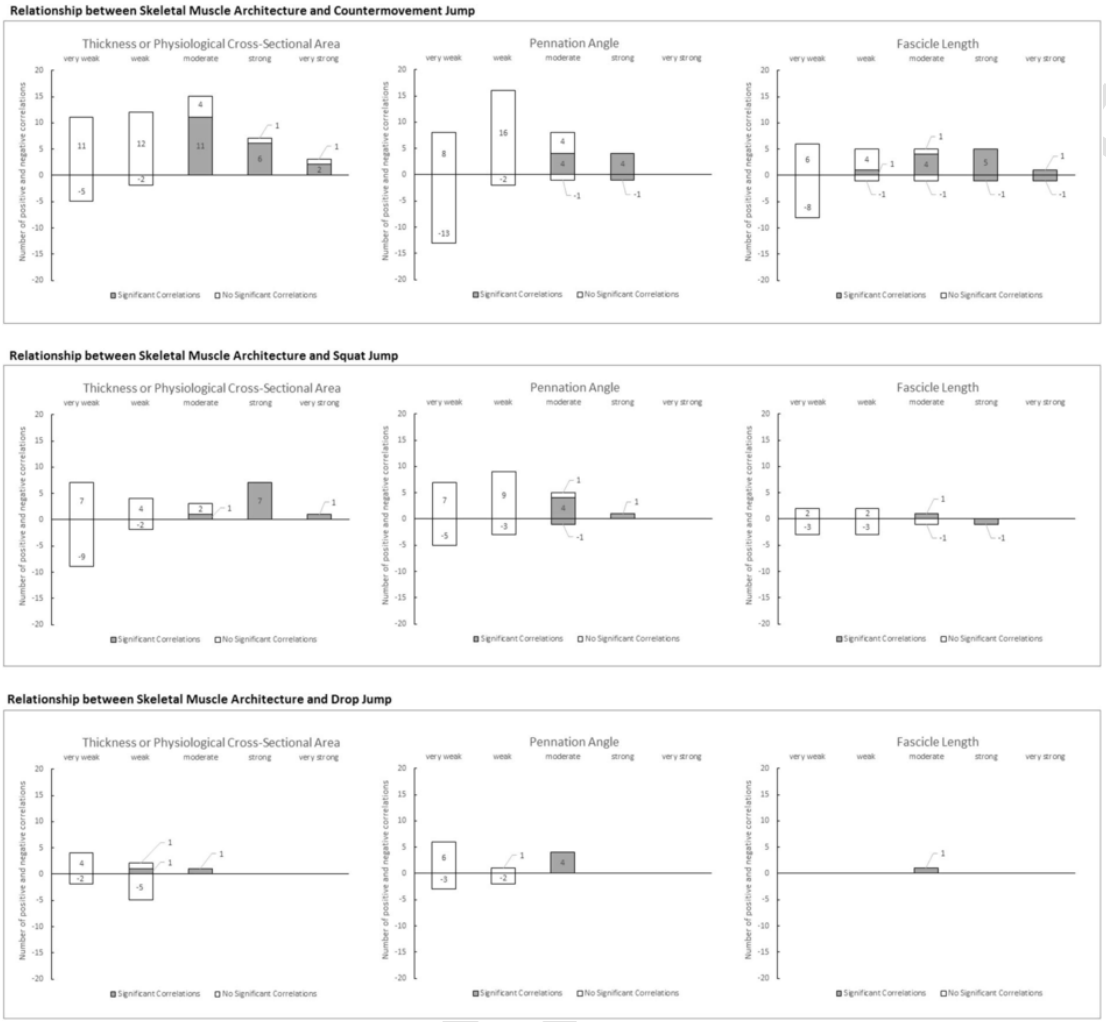

Fig. 2. Absolute frequencies of Pearson's correlation coefficients for the included studies. The x-axis shows the strength of correlations raging from very weak to very strong and the y-axis shows the number of significant (grey bars) and non-significant (white bars) correlations. Positive frequencies represent direct correlations while negative frequencies represent inverse correlations.

sis ($\chi^2 = 0.45$; df = 2; p = .80) with a low heterogeneity ratio ($I^2 = 0\%$) indicating similar association between SMA of VL during CMJ and SJ.

3.4. Study risk of bias

The degree of protocol description was good in general, although some parameters were insufficiently described. The subject position was clearly described for all eleven studies, but the clear anatomic localization where the probe was placed was explicit in eight studies (Alegre et al., 2009; Dobbs et al., 2015; Earp et al., 2011; Methenitis et al., 2016; Rodríguez-Juan et al., 2015; Secomb, Lundgren et al., 2015; Secomb, Nimphius et al., 2015; Selva Raj et al., 2017). The critical aspect of the description of the ultrasound parameters such as depth, localization of focuses or the use of gain curves was only clearly described by one study (Rodríguez-Juan et al., 2015). Four studies (Dobbs et al., 2015; Earp et al., 2010; Earp et al., 2011; Secomb, Nimphius et al., 2015) did not explain the method of measurement of the architectural parameters and only five (Alegre et al., 2009; Methenitis et al., 2016; Secomb, Lundgren et al., 2015; Secomb, Nimphius et al., 2015; Selva Raj et al., 2017) studies reported the reliability of measurements.

4. Discussion

This systematic review included eleven studies evaluating the relationship between SMA assessed with the ultrasound technique and jumping performance. It is noteworthy that no significant relationships were observed between SMA and jumping abilities during CMJ, SJ, and DJ in three quarters of included studies and only a quarter of the relationships were significant within a range of

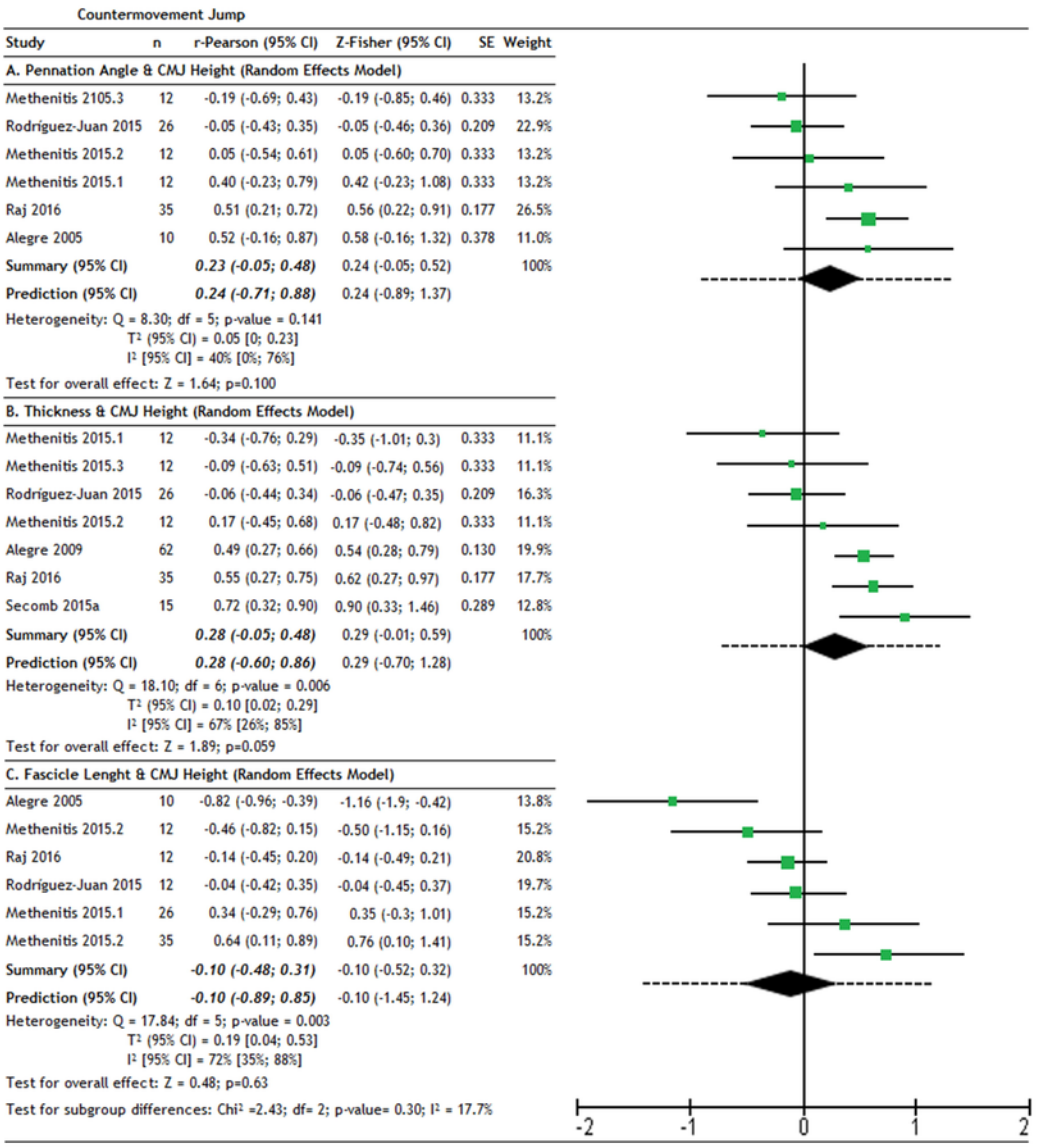

Fig. 3. Forest plots: Relationship between vastus lateralis muscle architecture and maximal jump height during Counter-movement Jump. *n*: sample size of studies. *95% CI*: 95% Confidence interval. *SE*: standard error. The forest plot shows in the x-axis the magnitude and direction of the associations and its variance (Fisher's z distribution and 95% CI) and the y-axis at 0 represents no association between variables. The size of the squares is proportional to the weight of the sample sizes of the included studies. The black diamonds represent the summary effect of correlations with the predictions intervals (dashed line). *Q*: Q-statistic that represents the weighted sum of squares on a standardized scale. *df*: degrees of freedom in Chi-squared distribution test. T^2: tau-squared statistic that represents the variance of the true effects and is used to assign study weights under the random effects model. I^2: The proportion of observed dispersion that is real.

moderate to very strong. Since moderate to very strong correlations were shown between SMA and jumping abilities regardless of the subject's physical condition or the outcome measured (jump height, power, velocity, force or rate of force developed), it is unclear why only 25% of correlations were moderate to very strong. However, the VL muscle showed more strong correlations than other muscles maybe because it was the most analyzed muscle (54%, 135/250 correlations). Nevertheless, most correlations showed trivial to moderate findings.

These observations have been reinforced by the results of the meta-analysis that was carried out to analyze the influence of muscle architectural features on vertical jumping performance with the most measured variables across studies; architectural features of VL (pennation angle, muscle thickness, and fascicle length) and maximal jump height during CMJ and SJ. Although the results in relation to muscle thickness for CMJ height showed a weak positive overall correlation (summary-r coefficient 0.28), the 95% CI of the summary-r coefficient is too wide to support the notion that muscle thickness would have an impact on jump height with sufficient confidence.

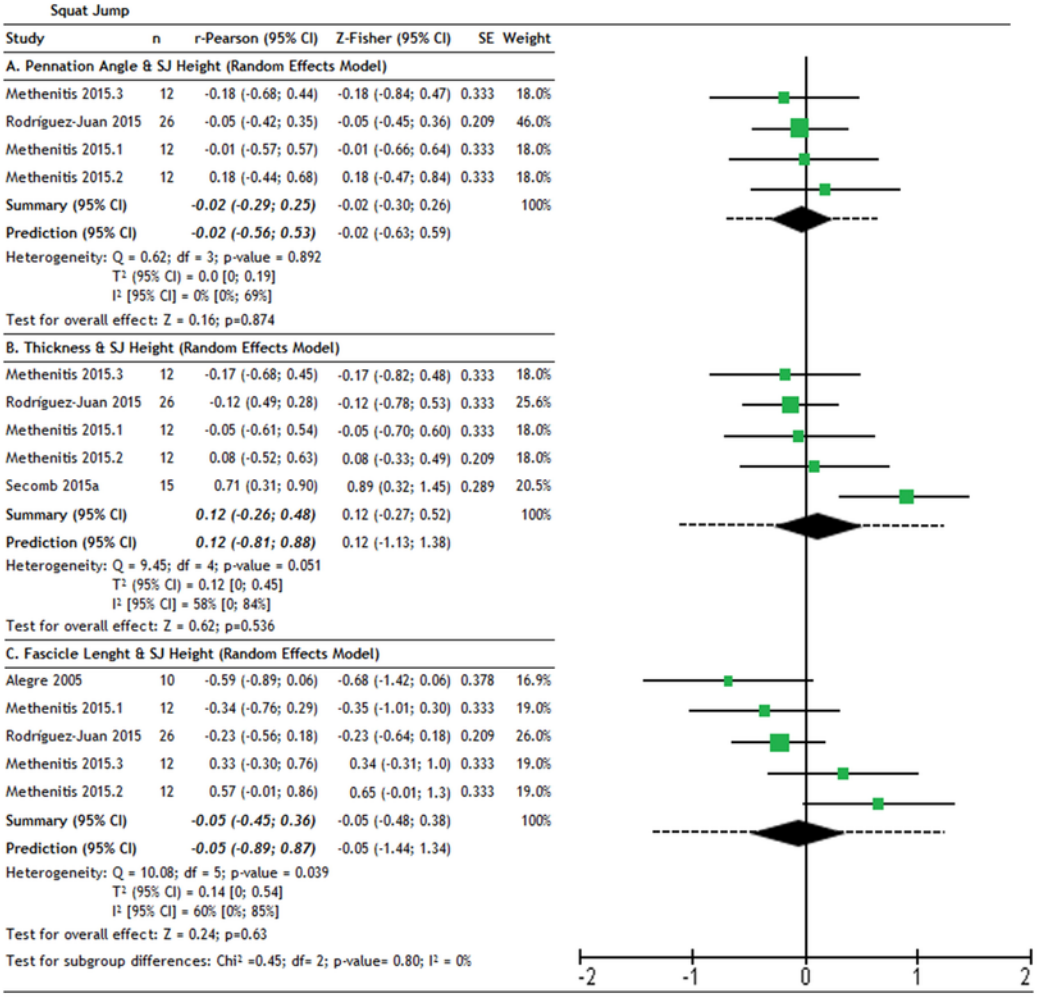

Fig. 4. Forest plots: Relationship between vastus lateralis muscle architecture and maximal jump height during Squat Jump. *n*: sample size of studies. *95% CI*: 95% Confidence interval. *SE*: standard error. The forest plot shows in the x-axis the magnitude and direction of the associations and its variance (Fisher's z distribution and 95% CI) and the y-axis at 0 represents no association between variables. The size of the squares is proportional to the weight of the sample sizes of the included studies. The black diamonds represent the summary effect of correlations with the predictions intervals (dashed line). *Q*: Q-statistic that represents the weighted sum of squares on a standardized scale. *df*: degrees of freedom in Chi-squared distribution test. T^2: tau-squared statistic that represents the variance of the true effects and is used to assign study weights under the random effects model. I^2: The proportion of observed dispersion that is real.

There was a moderate ratio of heterogeneity between studies. Since determining the angle of pennation and muscle thickness using the ultrasound technique is quite simple and consistent (Kwah et al., 2013; Raj, Bird, & Shield, 2012), the heterogeneity between studies with regard to these variables may be due to differences between subjects characteristics. However, the heterogeneity for muscle fascicle length was higher during both types of jump compared to muscle thickness or pennation angle. These findings could be due to the fascicle of human VL being too long (range between 6.4 and 12.2 cm) to capture through a single image obtained using a commercial ultrasound device. This measurement is normally estimated outside of the B-mode image capture, which could explain the large variations in length between authors (Alegre et al., 2005; Methenitis et al., 2016; Rodríguez-Juan et al., 2015; Secomb et al., 2015). This issue could be minimized by applying new technologies that allow scanning of the entire fascicles within one continuous scan (Noorkoiv, Stavnsbo, Aagaard, & Blazevich, 2010) or with appropriates methods of fascicle length estimation (Ando et al., 2014). The trigonometric method used to estimate the length of VL muscle fascicle by the studies included in our meta-analysis underestimates significantly the muscle fascicle length and shows a difference in length of 15.5% with an intra-class correlation coefficient of 0.048 with respect to direct measurement in cadavers (Ando et al., 2014).

Numerous researchers have debated the underlying mechanisms for the differences in jumping performance during countermovement and non-countermovement jumps, yet the causes are not well understood (Anderson & Pandy, 1993; Bobbert & Casius, 2005; Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Van Hooren & Zolotarjova, 2017). Considering the potential effect on jump height during CMJ due to stretch-shorten cycle and the storage of elastic energy, one could expect smaller associations between SMA fea-

tures and jump height during CMJ compared to SJ. However, the results provided by the selected studies and the meta-analysis have shown similar influence of SMA features on both jump modalities. Therefore, the potential effect on jumping abilities during CMJ may be mainly due to the tendon mechanical properties or neuromuscular activation (Bobbert, 2001; Bosco, Viitasalo, Komi, & Luhtanen, 1982; Kubo, Kawakami, & Fukunaga, 1999) rather than SMA of lower limbs.

Consequently, the results of this systematic review and meta-analyses did not support the concept of SMA as a crucial aspect for maximizing jumping performance in humans. Even taking into account the moderate baseline association shown by the authors between several muscle architecture features and biomechanical variables of jumping (Fig. 2), the Pearson's correlation coefficients imply a linear association between two variables but not a causation of both and these associations could be spurious (Altman & Krzywinski, 2015). Moreover, no study included in this systematic review adjusted the type I error for multiple analyses, therefore the level of statistical significance in the correlations could not be suitable (Curran-Everett, 2000). For example, when performing multiple correlation analyses between one architectural muscle feature and fourteen outcomes (Selva Raj et al., 2017) the probability of having p-value $< .05$ by chance for at least one of the outcomes is 51.4%. This issue is very important to consider when performing multiple correlation analyses and it is necessary for authors to use a statistical correction (Stovitz, Verhagen, & Shrier, 2016).

Although a simple correlation analysis can be interesting to detect associations between variables, when the objective is to explain complex variables such as jump, it is necessary to design a multivariate study with enough statistical power. The statistical power of studies depends on the sample size which is related to the amount of variance. The sample size of included studies was small, and the statistical power is limited (see confidence intervals in Figs. 3 and 4). Further studies with greater sample size and including multivariate analyses are necessary to better understand the influence of SMA on jumping performance in humans.

If jump performance was determined by muscle architecture, one would think that changes in muscle architecture could be reflected in changes in jumping performance. Nevertheless, the relevant literature on this topic is not consistent (Blazevich, Gill, Bronks, & Newton, 2003; Bloomquist et al., 2013; Cormie, McGuigan, & Newton, 2010; Fouré, Nordez, McNair, & Cornu, 2011; Keitaro Kubo et al., 2007). Blazevich et al. (2003) showed increases in VL muscle thickness and fascicle length without improvements in maximal jump height after 5 weeks of resistance training program. In contrast, Fouré et al. (2011) reported increases in maximal jump height during SJ and CMJ but no changes were observed in CSA of triceps surae muscle, pennation angle and fascicle length of lateral gastrocnemius, medial gastrocnemius, and soleus during 14 weeks of plyometric training program. Another study reported differences in maximal jump height during SJ and CMJ after 12 weeks of progressive squat training without changes in VL muscle thickness. While VL pennation angle increased, no correlations were found between jump performance and muscle architecture (Bloomquist et al., 2013). Finally, Cormie et al. (2010) reported increases in jump height in both weaker and stronger group of individuals after 10 weeks of jump squat training program without changes in VL muscle thickness and pennation angle. Although the aforementioned evidence does not suggest that muscle architecture can be highly determinant of jumping performance, these observations should be taken with caution. Since muscle geometry is not fixed for a given muscle but dynamic changes occur during a contraction, the visualization of architecture in non-contracted, static muscle may not allow inference of muscle function during dynamic, active movements. However, the scientific evidence relative to the validity of B-mode ultrasonography measures when images are obtained dynamically during jumping is limited (although apparently reliable) (Kurokawa, Fukunaga, & Fukashiro, 2001).

The possibility that changes in muscle architecture can modify jumping performance may exist but the current data do not support this premise. It is very hard to explain performance during jumping through the influence of muscle architecture of one single muscle in one single leg. In other words, a small biological characteristic of a muscle may not be representative of the overall function of the neuromuscular system during a complex motor task and its influence could be minimal. Recently, Trezise, Collier, and Blazevich (2016) analyzed the influence of multiple anatomical and neuromuscular variables on maximum knee extensor torque. Although an apparently inconsequential correlation (weak correlation) and non-significant correlations were found between several muscle architectural features and torque production, the inclusion of these variables together with neuromuscular variables (percent of voluntary activation or patellar tendon moment arm distance, among others) into predictor models revealed the best prediction of knee extensor torque. These results highlight the importance of examining interactions between variables of SMA features rather than assessing correlations in isolation supporting the aforementioned idea.

From this systematic review and meta-analysis, we encourage future research to better understand the relationship between muscle architectural features and jumping performance in humans. The studies could be designed assessing a set of muscle architecture variables in several lower limb muscles and employing prediction models of jumping performance, similar to Trezise et al. (2016). Another idea could be to use dynamic ultrasonography measures during jumping (Kurokawa et al., 2001) in participants with different muscle architectural characteristics.

Despite a rigorous approach towards data collection and synthesis, this review is not without limitations. Only eleven studies were included in this systematic review which had a low reproducibility; most studies did not report the reliability of their measurements. Studies were heterogeneous concerning participant position and probe location on the muscle group which could vary the results. There was insufficient data to perform meta-analysis on muscles other than VL for CMJ and SJ. Therefore, the analysis does not represent the whole function of the lower limb muscles. As mentioned above, association does not imply causation and the baseline relationship between muscle architectural features and biomechanical jumping variables could not be presented since the present meta-analysis is based on cross-sectional data. The strength of systematic reviews is that by systematically identifying these limitations, future designs can be improved to better understand the relationship between muscle architectural features and jumping performance.

5. Conclusion

Current evidence based on simple correlations between SMA of lower limb muscles and vertical jumping performance in humans does not suggest a great influence on vertical jumping. Only 25% of all correlations were moderate to very strong while the most correlations showed trivial and non-significant findings. VL muscle thickness showed a weak relationship with jump height during CMJ but the confidence interval is too wide to support the notion that muscle thickness would have an impact on jump height with sufficient confidence. The statistical methods used by the included studies could not be suitable for evaluating influences between SMA and a complex motor task such as jumping. Caution should be taken when extrapolating measurements made on static muscle architecture features to whole-muscle function. Muscle architectural features measured by 2-D ultrasonography could not be useful as a predictor of jumping performance in humans.

Conflict of interest

None.

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