Child-Adult differences in antagonist muscle coactivation: A systematic review

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Abstract

Antagonist coactivation is the simultaneous activation of agonist and antagonist muscles during a motor task. Age-related changes in coactivation may contribute to observed differences in muscle performance between children and adults. Our aim was to systematically summarize age-related differences in antagonist muscle coactivation during multi-joint dynamic and single-joint isometric and isokinetic contractions. Electronic databases were searched for peer-reviewed studies comparing coactivation in upper or lower extremity muscles between healthy children and adolescents/young adults. Of the 1083 studies initially identified, 25 met eligibility criteria. Thirteen studies examined multi-joint dynamic movements, 10 single-joint isometric contractions, and 2 single-joint isokinetic contractions. Of the studies investigating multi-joint dynamic contractions, 83% (11/13 studies) reported at least one significant age-related difference: In 84% (9/11 studies) coactivation was higher in children, whereas 16% (2/11 studies) reported higher coactivation in adults. Among single-joint contractions, only 25% (3/12 studies) reported significantly higher coactivation in children. Sixty percent of studies examined females, with no clear sex-related differences. Child-adult differences in coactivation appear to be more prevalent during multi-joint dynamic contractions, where generally, coactivation is higher in children. When examining child-adult differences in muscle function, it is important to consider potential age-related differences in coactivation, specifically during multi-joint dynamic contractions.

Key words: Antagonist muscle, Contraction, Co-contraction, EMG, Maturation

Introduction

Muscle performance is lower in children compared with adults even after accounting for differences in body size (Armatas et al., 2010; De Ste Croix et al., 1999; Falk et al., 2009b). For example, children have lower size-corrected maximal and explosive strength compared with adults (Falk et al., 2009a, 2009b). One factor suggested to contribute to these growth-related changes in performance is greater antagonist muscle coactivation in children compared with adults (Grosset et al., 2008; O'Brien et al., 2009). Coactivation is the simultaneous activation of an antagonist muscle during an agonist muscle action. There are several studies which have investigated antagonist coactivation in children and adults, during isometric, (Falk et al., 2009a, 2009b; Grosset et al., 2008; Hassani et al., 2009; Jensen et al., 2013; Kochanowiz et al., 2018; Kotzamanidou et al., 2005; Lambertz et al., 2003; Morse et al., 2008; O'Brien et al., 2009, 2010) isokinetic (Bassa et al., 2005; Kellis and Unnithan, 1999) or multi-joint dynamic movements of the upper or lower extremities (Croce et al., 2004; Deffeyes et al., 2012; Frost et al., 2002, 1997; Lazaridis et al., 2010, 2013; Thompson-Kolesar et al., 2018), with inconsistent results. Some studies report greater coactivation in children (Frost et al., 2002; Grosset et al., 2008; Lazaridis et al., 2010), some report greater coactivation in adults (Kochanowiz et al., 2018; Oliver and Smith, 2010; Quinzi et al., 2015), while others report no age-related differences (Deffeyes et al., 2012; Falk et al., 2009b; Jensen et al., 2013; O'Brien et al., 2010; Raffalt et al., 2017). Further, some studies report age-related differences in antagonist coactivation in some but not all movements (Kochanowiz et al., 2018; Lazaridis et al., 2013; Thompson-Kolesar et al., 2018). Thus, while it is commonly accepted that antagonist coactivation, in general, is greater in children and decreases with age, the inconsistent findings reported in the above studies, where different types of movements or contractions were examined, bring this certainty into question.

All movements involve some level of coactivation. It has been suggested that the main purpose of antagonist muscle coactivation is to provide stability to the joints on which strain is applied (Baratta et al., 1988; DeLuca and Mambrito, 1987; Solomonow et al., 1987). The extent of antagonist coactivation is influenced by factors such as the contraction type and intensity (Pincivero et al., 2019), velocity (Frost et al., 1997), muscle group and joint(s) being assessed (Kochanowiz et al., 2018), as well as the training status of the participant (Carolan and Cafarelli, 1992). Generally, antagonist coactivation is lower during isometric contractions than dynamic contractions (O'Brien et al., 2010; Quinzi et al., 2015). Therefore, child-adult differences in antagonist coactivation may depend on the type of task being performed. While providing stability is beneficial, coactivation may be detrimental to force production or efficiency of movement. For example, during single-joint isometric contractions, relatively high coactivation of the antagonist will detract from the force produced by the agonist (Kellis and Baltzopoulos, 1997). Thus, it is possible that children's lower maximal force production, or greater muscle activation during submaximal contractions may be partly explained by greater antagonist coactivation (Miller et al., 2019). During multi-joint dynamic contractions (e.g., gait), high levels of antagonist coactivation cause inefficient movement (Frost et al., 1997). Thus, it is possible that previously reported greater metabolic cost of locomotion in children is at least partly explained by greater levels of antagonist coactivation (Allor et al., 2000).

The purpose of this study was to systematically gather and compile studies examining child-adult differences in coactivation during various muscular tasks, to examine whether coactivation differs between children and adults. Secondly, to examine whether age-related differences in coactivation are influenced by contraction type (i.e., multi-joint dynamic vs. single-joint isometric and isokinetic).

Methods

Literature search

A search of MEDLINE (OVID), MBASE (OVID), SPORTDiscus (EBSCO), Web of Science (Core Collection), and BIOSIS (Web of Science) databases was performed on February 26, 2021 to identify pertinent studies. The combination of keywords and/or phrases (mp) and MeSH terms (/) relevant to "children" (Child/ child*mp, boy*mp, girl*mp, adolescen*mp, youth*mp, juvenile*mp, minor*mp, paediatric*mp, paediatric*mp, pediatric*mp, puber*mp, pubescen*mp, underage*mp, under-age*mp, teen*mp, or prepubert*mp, and school child [in EMBASE (OVID) only]), "adults" (Adult/ adult*mp, men*mp, man*mp, women*mp, woman*mp, female*mp, or male*mp, and middle aged or young adult [in EMBASE (OVID) only]), "coactivation" (coactivation*mp, co-activation*mp, cocontraction*mp or co-contraction*mp), and "muscle" (muscle*mp, agonist*mp or antagonist*mp) were used to search for relevant articles.

When the search was complete, all publications identified in the search were uploaded into software for citation management (Zotero) and screening (Covidence). Following the removal of duplicates, two reviewers (SW, CO) independently screened the titles and abstracts for relevant articles, and conflicts were resolved by an additional reviewer (BF). Two reviewers (SW, CO) then screened the full text of the remaining articles to assess eligibility. At this time the reference lists were also screened to identify any relevant articles that were missed in the search. Conflicts among reviewers were resolved by an additional reviewer (BF).

Inclusion criteria

Studies were included in the review if they assessed coactivation or co-contraction of lower or upper extremity muscles in healthy children and adolescents/adults. In studies which included an intervention, only baseline values were extracted. In cases where data were presented in figures only, group means and standard deviations were estimated using Web Plot Digitizer (Drevon et al., 2017). No limits were placed on the year of publication and only full text articles published in English were identified.

Quality assessment: Risk of Bias

Risk of bias was assessed using the Appraisal tool for Cross-Sectional Studies (AXIS tool) (Downes et al., 2016) and Quality Assessment Tool for Quantitative Studies (Thomas et al., 2004). Some items were removed, as they were not relevant for cross-sectional studies with no intervention. The assessment tools were used to evaluate the following qualities: [1] Sampling/target population, [2] design, [3] procedures, [4] statistical analysis, [5] reporting of findings, [6] reporting withdrawals/non-responders, [7] possible bias from funding sources. For the Thomas et al., (2004) assessment, studies were ranked ‘strong’, ‘moderate’, or ‘weak’. For the Downes et al., (2016) assessment, studies were classified as either “meeting” the criteria (‘yes’) or “not meeting” the criteria (‘no’). The risk of bias assessment was completed for all studies by two researchers independently (AM, SW), and disagreements were resolved by consensus.

Data extraction and analysis

From the included studies, sample size, participant characteristics (sex, age, and pubertal stage or maturational status for the children), muscle group examined, task or contraction type, calculation method, and coactivation values (group means and SD or SE) were extracted by two authors independently (SW, CO). Conflicts were resolved by consensus. All the extracted data were compiled into 3 tables and organized based on contraction type (Tables 1-3), where each comparison was listed separately. Studies investigating isometric and isokinetic contractions were categorized as ‘single-joint’ contractions, whereas studies examining dynamic movements such as jumping, balancing, or gait were categorized as ‘multi-joint’.

Results

From the initial search, 1083 articles were identified. Following the removal of duplicates, 602 titles and abstracts were screened for relevance. Of these articles, 33 were fully assessed for eligibility. During this process, 3 additional studies were identified in the reference lists. From the 36 articles, 11 full-text articles were excluded for one of the following reasons: [a] study did not examine or report antagonist coactivation for both child and adult groups, [b] study did not report original data and data were not able to be obtained from the corresponding author. Thus, of the studies assessed, 25 were included in the review.

[Figure 1. PRISMA flowchart]

The studies included comprised 427 children (7-13 year) and 337 adolescents/adults (15-40 years). Of the 25 studies included, 12 examined both males and females, 11 examined males only, and 2 examined females only. Ten studies investigated isometric contractions, 2 studies examined isokinetic contractions and 13 studies examined dynamic tasks such as jumping, hopping, walking, running, standing and change of direction movements (i.e., sports cuts). The 25 studies included 158 age-related comparisons. Among these 158 comparisons, most (82%, 129/158 comparisons) suggested greater antagonist coactivation in children, although only 45% (58/129 comparisons) of these reached statistical significance. Twenty-nine comparisons (18%, 29/158 comparisons) suggested greater antagonist coactivation in adults, although only 24% (7/29 comparisons) of these reached statistical significance.

Of the ten studies examining isometric contractions, 2 studies examined elbow flexors and extensors, 1 study examined elbow and shoulder flexors and extensors, 4 studies examined knee extensors and flexors, and 3 studies examined the plantar- and dorsi-flexors. Within the 10 studies, there were 30 comparisons of antagonist coactivation between children and adults. In 30% (3/10) of studies (43% or 13/30 of comparisons) antagonist coactivation was statistically greater in children compared with adults. In one study (2 comparisons), antagonist coactivation was higher in adults (Table 1)(Kochanowiz et al., 2018).

Two studies examined antagonist coactivation of the knee extensors and flexors during isokinetic contractions in children and adults, reporting 14 comparisons in total. In all comparisons, there were no significant differences in antagonist coactivation between children and adults.

[Table 1]

Thirteen studies investigated antagonist coactivation of the lower limb muscles during multi-joint dynamic contractions, resulting in 114 comparisons between children and adults. All but two studies reported significant age-related differences in antagonist coactivation in at least some of the comparisons (Lloyd et al., 2012; Oliver and Smith, 2010). In 35% (40/114) of comparisons coactivation was significantly higher in children, while in 4.4% (5/114) of comparisons, antagonist coactivation was significantly higher in adults. That is, in most cases in which a significant age-related difference was reported, antagonist coactivation was higher in children (Tables 2 and 3).

[Tables 2 and 3]

Risk of bias

Based on the Thomas et al., (2004) risk of bias assessment, 21 studies rated moderate and 4 studies rated weak in terms of selection bias. Two studies rated strong, 18 moderate and 5 weak in terms of controlling of confounding variables. Only one study was rated as moderate in terms of using blinding procedures during the data analysis. All studies rated strong in terms of using valid and reliable data collection methods. Lastly, all studies rated weak in terms of reporting withdrawals and/or dropouts from the study.

When using the Downes et al., (2016) risk of bias assessment, all studies had clear aims/objectives, appropriate study design, and valid measures and instrumentation. Similarly, in all studies, procedures were cleared by an ethics board, outcome variables were adequately described in the methods and results, findings were internally consistent, and conclusions were justified by the results. There were no studies where the response rate raised concerns about non-response bias and no studies reported funding sources or conflicts which may affect the authors interpretation of the results. Only one study justified its sample size. All but one study provided clear and sufficient description of the experimental and statistical procedures. Twenty-two studies clearly defined their target population, and 4 studies recruited from a wider population than was defined. Moreover, in 4 studies it was unclear where participants were recruited. Only 2 studies disclosed information about non-responders or cases where coactivation could not be calculated. Lastly, only 13 studies discussed limitations.

Discussion

This is the first study to systematically examine child-adult differences in antagonist muscle coactivation during various muscle contractions. We identified 25 studies, comprising 158 comparisons. Overall, there was no clear pattern of greater (or lower) antagonist muscle coactivation in children. However, a clearer pattern was apparent when age-related differences in coactivation were examined by contraction type (multi-joint dynamic vs. single-joint isometric or isokinetic). There was greater prevalence of age-related differences in antagonist muscle coactivation in multi-joint dynamic tasks (83%; 9/13 studies), and less in single-joint, isometric or isokinetic tasks (25%, 3/12 studies). With few exceptions, coactivation was higher in children. Overall, theses findings suggest that child-adult differences in antagonist muscle coactivation are task-specific and may be greater during multi-joint dynamic tasks, compared with single-joint isometric and isokinetic tasks. Such age-related differences may contribute to children's lower efficiency of movement and muscle performance.

Role of coactivation in multi-joint dynamic tasks

Antagonist muscle coactivation plays an important role in the stabilization of joints, particularly during uncontrolled dynamic movements (Baratta et al., 1988; Solomonow et al., 1987). In all but two studies examining multi-joint dynamic contractions, higher antagonist coactivation was reported in children during at least one of the experimental conditions (Frost et al., 2002, 1997; Kurz et al., 2018), or movement phases (e.g., breaking phase of a jump landing; Lazaridis et al., 2013). In such conditions, children's greater antagonist muscle coactivation may explain, at least partly, their lower movement efficiency (e.g., in gait, hopping; Allor et al., 2000). For example, Frost et al., (2002, 1997) examined age-related differences in lower- and upper-leg antagonist coactivation during gait at various speeds in children and adolescents, reporting higher coactivation index in younger children compared with older adolescents, specifically at higher speeds. The authors suggested that greater antagonist coactivation contributes to children's higher cost of locomotion, as demonstrated in several studies (Allor et al., 2000; Frost et al., 2002; Krahenbuhl and Williams, 1992; Rowland et al., 1987). Children's higher antagonist coactivation may also partially explain their lower performance during multi-joint dynamic tasks (e.g., countermovement jump height). For example, Lazaridis et al., (2010) reported higher lower-leg antagonist coactivation during a drop jump, along with lower jump height and ground reaction forces in boys compared with men. The authors argued that children's higher coactivation reflects "less stiffness regulation" (i.e., greater musculotendinous compliance and lower muscle activation) and immature jumping technique (Lazaridis et al., 2010, 2013).

Coactivation is regulated by a complex interaction of activation from central (i.e., motor cortex – pre-synaptic inhibition) and peripheral (i.e., reciprocal and recurrent inhibition) origins. Specifically, during dynamic movements such as jumping, stretch reflexes can decrease antagonist coactivation by reciprocal inhibition (Day et al., 1984; Mizuno et al., 1971). Grosset et al., (2007) demonstrated lower triceps surae stretch reflex response in children compared with adults, attributing it to children's immature sensitivity of the muscle spindles and γ-motor neurons and greater musculotendinous compliance. It is possible that children's higher coactivation reflects a lower reflex response and less reciprocal inhibition. Indeed, most age-related differences in antagonist coactivation were observed during multi-joint jumping tasks (e.g., counter movement jump and drop jump), where implications of the stretch reflex would be greatest. More research examining the age-related changes in the stretch reflex are needed to elucidate the role that the stretch-reflex plays in modulating antagonist coactivation in children.

While most of the age-related differences in antagonist coactivation were observed during dynamic, multi-joint tasks, it should be noted that in many movements no such differences were reported. One possibility is that age-related differences in coactivation are more apparent during tasks of higher difficulty (requiring technical skill; Gebel et al., 2019; Paschaleri et al., 2021). Classic motor-learning theory suggests that with increased experience or skill level (i.e., age), antagonist coactivation decreases (Ford et al., 2008). Along these lines, most of the studies reporting greater coactivation in children examined younger children and involved more complex tasks, such as drop jumps, (Croce et al., 2004; Lazaridis et al., 2010, 2013) or running at high velocities (Frost et al., 2002, 1997).

Role of coactivation during controlled, isometric and isokinetic tasks

Antagonist coactivation is also observed during controlled isometric or isokinetic contractions, during which it may attenuate muscle performance (e.g., maximal force, power; Kellis and Baltzopoulos, 1997). Along these lines, when trying to maintain a submaximal force level, Grosset et al., (2008) reported lower neuromuscular efficacy (inverse of EMG-force slope), and higher antagonist coactivation in children compared with adults. Miller et al., (2019) also suggested that children's greater antagonist coactivation during low-intensity submaximal contractions may explain their 'over activation' (i.e., higher motor-unit firing rates) of the agonist muscle. Nevertheless, most studies examining single-joint isometric/isokinetic contractions reported low antagonist coactivation and no difference between children and adults (Falk et al., 2009b, 2009a; Lambertz et al., 2003; O'Brien et al., 2010, 2009). Indeed, during isometric and isokinetic contractions, only 3 of 12 studies reported greater antagonist coactivation in children compared with adults (Grosset et al., 2008; Hassani et al., 2009; Kochanowiz et al., 2018). These inconsistent findings may be related to an unfamiliar movement [e.g., dorsi-flexion (Grosset et al., 2008)] or body position [prone (Hassani et al., 2009)], or muscle length – [long vs. short (Hassani et al., 2009)]. Further research is needed to examine other factors which may influence chid-adult differences in coactivation during relatively simple, single-joint isometric/isokinetic contractions.

The case for greater antagonist coactivation in adults

In some cases, coactivation may play an important role in joint stabilization, thereby minimizing the risk of injury. Kochanowiz et al., (2018) demonstrated that during shoulder flexion, antagonist coactivation is significantly greater in adults compared with children. This pattern was observed among gymnasts, as well as non-athletes. In view of the structural instability of the shoulder joint, such coactivation may be instrumental for reducing the risk of injury. Indeed, this was the only study examining isometric contractions in which children's coactivation was significantly lower than adults'. During multi-joint, dynamic contractions, only three studies reported statistically higher antagonist coactivation in adults compared with children at some (but not all) phases of the movement (Croce et al., 2004; Quinzi et al., 2015; Russell et al., 2007). Quinzi et al., (2015) reported greater coactivation in adult compared with adolescent karateka during the extension phase of a roundhouse kick. Notably, such a kick requires high angular velocity, which was greater in the adults, and results in high impact force (not measured but presumed higher in the adults). Thus, the authors argued that the adults' higher antagonist coactivation may be related to the presumed greater impact force and consequent stress imposed on the knee joint. This is in line with Russell et al., (2007) and Croce et al., (2004), who reported higher antagonist coactivation in adults compared with children immediately before landing from a drop jump. Thus, while in most cases antagonist coactivation is greater (or similar) in children compared with adults, in cases of joint structural instability, (Kochanowiz et al., 2018) or when impact is anticipated (Croce et al., 2004; Quinzi et al., 2015; Russell et al., 2007) greater coactivation may be observed in adults.

Sex differences in antagonist coactivation

In adults, several studies have demonstrated greater antagonist coactivation in women compared with men during single-joint concentric and eccentric contractions, as well as during jumping tasks (De Ste Croix et al., 2017; Krishnan et al., 2015; Marquez et al., 2017; Smith et al., 2021). Sex-differences in antagonist coactivation during the pubescent years are of particular interest, due the high prevalence of anterior cruciate ligament injuries among adolescent females (Hewett et al., 2006, 2004; Montalvo et al., 2019; Tursz and Crost, 1986). Five of the studies included in the present review specifically examined sex-related differences in antagonist coactivation in children and adults (Croce et al., 2004; Kellis and Unnithan, 1999; O'Brien et al., 2010, 2009; Russell et al., 2007). While sex-related differences in antagonist coactivation were not statistically significant, a pattern of higher antagonist coactivation among women compared with men was observed, with no such pattern in the children (Jensen et al., 2013; Kellis and Unnithan, 1999; O'Brien et al., 2010, 2009). This suggests that sex-related differences in coactivation likely develop during puberty. Future research should examine whether sex-related differences in antagonist muscle coactivation is related to maturity and potentially, the associated hormonal changes.

Methodological issues

One of the striking findings illustrated by this review is the tremendous variability amongst studies in the strategies used to quantify coactivation (Tables 1-3). Despite this variability, two main quantification strategies can be identified, associated with the type of contraction examined. In isometric contractions, coactivation is commonly calculated as the proportion of antagonist activation relative to its activation as an agonist (Bassa et al., 2005; Falk et al., 2009b; Kellis and Unnithan, 1999). In multi-joint dynamic tasks such as gait, jumping or hopping, coactivation is primarily derived from the ratio of activation (reflected in EMG amplitude) of the antagonist muscles to the agonist muscles over specific durations or phases of the task (Croce et al., 2004; Frost et al., 1997; Lazaridis et al., 2013; Russell et al., 2007). The different quantification approaches make it difficult to compare coactivation values between studies or between muscles. However, the strategy used to quantify coactivation should not influence the age-related comparison within each study, as an identical strategy is used for each age group. Nevertheless, it may be argued that the quantification approach could affect the magnitude of child-adult difference in coactivation. Kellis et al., (2003) examined the effect of 4 different calculation methods on coactivation during phases of drop jumps in adults. They found that the magnitude of coactivation and differences between drop heights and jump phases changed, depending on the calculation method used. However, the pattern of differences between drop heights or jump phases remained the same, regardless of the calculation method used. Ultimately, the authors recommend that researchers use the method which best reflects the examined tasks and research question. Of note, the above calculation approaches are based on EMG amplitudes from two muscles (i.e., one agonist and one antagonist) in the upper or lower limbs, acting on the same joint. Recently, the time-varying multi-muscle approach and vector coding technique have been developed to allow for the monitoring of more than two muscles, antagonists or synergists, throughout a movement task (Rinaldi et al., 2018)). These approaches have been used to examine coactivation among muscles of the trunk and lower extremities during dynamic movement tasks (Ranavolo et al., 2015; Rinaldi et al., 2020; Tatarelli et al., 2020). Moreover, they seem to provide a more sensitive estimate of antagonist coactivation (Rinaldi et al., 2018) during dynamic tasks, better differentiating between varying loads (Ranavolo et al., 2015), and may be useful in better detecting age-related differences in antagonist coactivation. The Vector Coding Technique was recently used to demonstrate increasing antagonist coactivation during gait in children with muscular dystrophy (Rinaldi et al., 2020), but to our knowledge, has not been applied in healthy children.

Another factor contributing to the variability in the coactivation values between studies is related to the normalization of the EMG signal. Normalization is often used to reduce the large inter-subject variability (Winter and Yang, 1984). This approach was adopted in many of the studies reviewed in this study, particularly in dynamic contractions, although the reference value used for normalization varied between studies (Croce et al., 2004; Frost et al., 2002, 1997; Lazaridis et al., 2010, 2013; Oliver and Smith, 2010; Russell et al., 2007; Thompson-Kolesar et al., 2018). For example, Thompson-Kolesar et al., (2018) used maximal EMG root mean squared (RMS) achieved during specific movements (e.g., running, squat jumps, resisted knee flexion and extension) to normalize EMG RMS obtained during the studied jumping and sports cutting tasks. Oliver and Smith, (2010) on the other hand, used total activation during the ground contact period to normalize the integrated EMG measured during various hopping phases. These different normalization procedures influence the magnitude of the calculated coactivation, and may also affect between-group differences (Katsavelis and Joseph Threlkeld, 2014). In adults, Katsavelis and Joseph Threlkeld, (2014) compared seven different normalization approaches, using the peak EMG RMS, the average EMG RMS during discrete phases, or the average EMG RMS during the entire maximal isometric knee extension. They found that normalizing EMG RMS to the RMS during the 500ms interval around peak torque resulted in the lowest variability and highest reliability within and between testing sessions. It is well documented that size-normalized peak torque is lower in children compared with adults (De Ste Croix et al., 1999; Falk et al., 2009a) and the associated EMG RMS is also lower. Therefore, it is possible that the approach recommended by Katsavelis and Joseph Threlkeld (2014) (i.e. normalizing to EMG RMS during peak torque production) may differentially affect the resultant calculated antagonist coactivation in children and adults.

Finally, technical issues in EMG recording (e.g., signal-to-noise ratios) and processing (e.g., filter cut-off frequencies) may also affect the variability and sensitivity of antagonist coactivation estimation, as elegantly demonstrated by Rinaldi et al., (2018). Traditional approaches to quantifying antagonist coactivation can be influenced by such technical issues, while more recent approaches using time-varying multi-muscle estimations or Vector coding appear to be more sensitive and robust. The sensitivity of these approaches has been demonstrated in adults, using different lifting loads (Ranavolo et al., 2015) or simulations (Rinaldi et al., 2018). In children, overall signal amplitude is generally lower and signal-to-noise ratios are often lower than in adults. Thus, future studies investigating age-related changes in antagonist coactivation and potential mechanisms would benefit from the use newer approaches to estimate coactivation.

Conclusions

The present review systematically compiled 25 studies examining child-adult differences in antagonist coactivation during single-joint isometric and isokinetic tasks and multi-joint dynamic tasks of the upper and lower extremities. In most cases, coactivation was higher in children than in adults, although statistical significance was reached in only 45% of comparisons. Most studies of dynamic multi-joint contraction tasks reported significantly higher antagonist coactivation in children. Overall, these findings suggest that higher antagonist coactivation in children may affect muscle performance (maximal force, efficiency), primarily in dynamic contractions and less so in single-joint isometric and isokinetic contractions. It is unclear whether age-related differences in coactivation differ between males and females, but if so, they are more likely among post-pubescents and adults. Future studies need to use robust algorithms to examine potential mechanisms underlying age-related changes in coactivation, which may involve children's greater musculotendinous compliance, lower neuromuscular activation, and developing skill level.

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Figure legends

Figure 1. PRISMA flow chart of study inclusion.

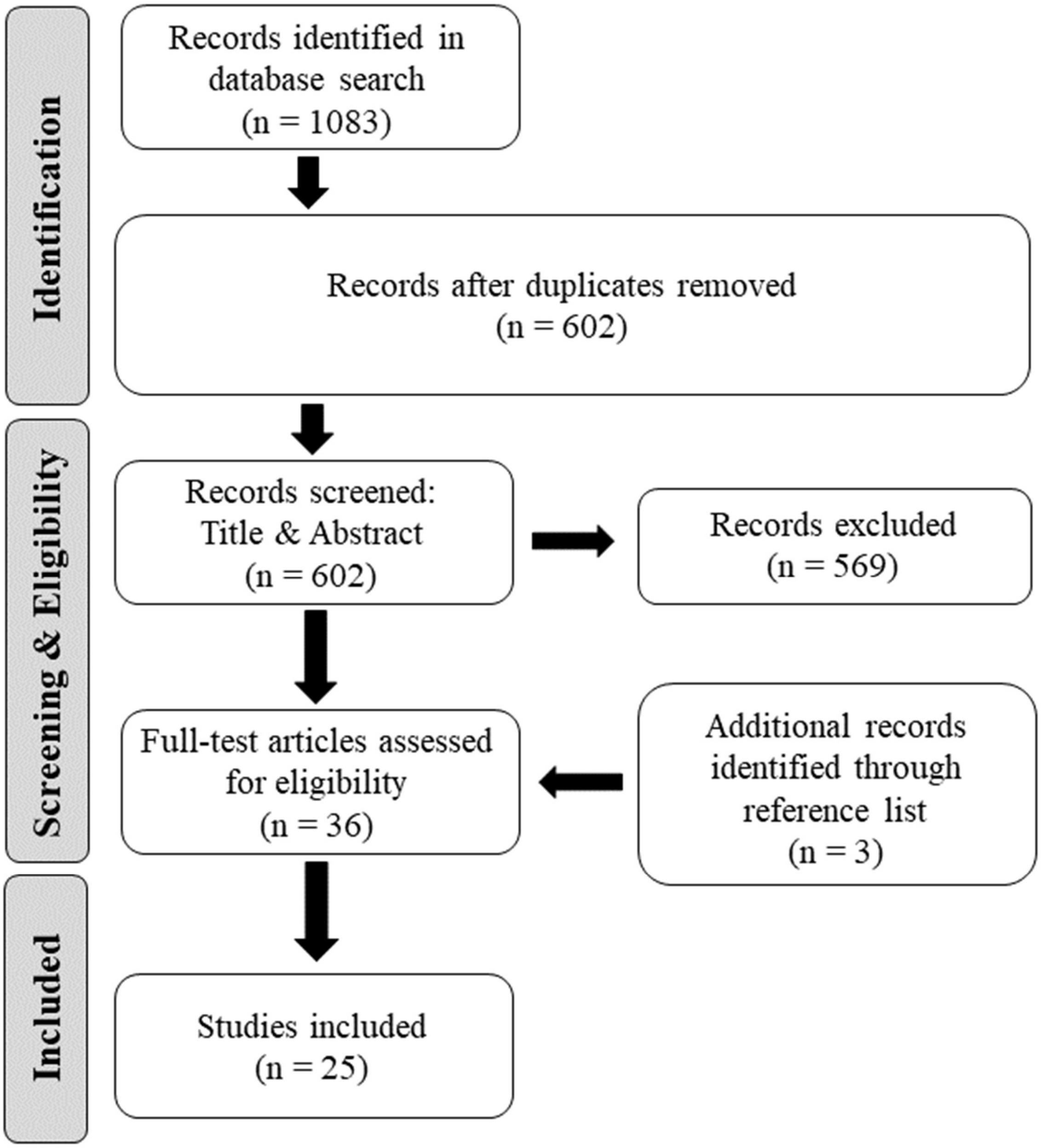

Identification
Screening & Eligibility
Included
Records identified in database search (n = 1083)
Records after duplicates removed (n = 602)
Records screened: Title & Abstract (n = 602)
Records excluded (n = 569)
Full-test articles assessed for eligibility (n = 36)
Additional records identified through reference list (n = 3)
Studies included (n = 25)

Table 1. Single-Joint – Isometric and Isokinetic Comparisons. Values are mean±SD, unless otherwise indicated

Study	**Sex**	**Participants n (age, year)**		**Muscle studied**	**Contraction task**	**Calculation method**	**Coactivation (%)**		**Statistically significant**
		Children	**Adults**				**Children**	**Adults**	
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	CON - 45°/s Extension	Ant/Ag	0.14±0.02δ	0.16±0.02δ	No
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	CON - 90°/s Extension	Ant/Ag	0.16±0.02δ	0.18±0.04δ	No
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	CON - 180°/s Extension	Ant/Ag	0.23±0.03δ	0.19±0.03δ	No
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	ECC - 45°/s Extension	Ant/Ag	0.13±0.015δ	0.13±0.02δ	No
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	ECC - 90°/s Extension	Ant/Ag	0.13	0.13	No
Bassa et al., (2005)†	M	18(10.9±0.6)δ	13(18.1±0.1)δ	BF	ECC - 180°/s Extension	Ant/Ag	0.125	0.13	No
Falk Usselman et al., (2009)	M	9(9.6±1.6)	9(22.1±2.8)	TB	Maximal Iso Flexion	Ant/Ag	0.59±0.44	0.44±0.27	No
Falk Usselman et al., (2009)	M	9(9.6±1.6)	9(22.1±2.8)	BB	Maximal Iso Extension	Ant/Ag	0.09±0.06	0.12±0.07	No
Falk Brunton et al., (2009)	F	10(9.1±1.4)	15(21.5±0.6)	TB	Maximal Iso Flexion	Ant/Ag	0.3±0.12	0.3±0.2	No
Jensen et al., (2013)†	M/F	20 (10.2±0.4)	18 (40.3±4.1)	BF	25% MVC Flexion	Ant/Ag	11.04	7.64	No
Jensen et al., (2013)†	M/F	20 (10.2±0.4)	18 (40.3±4.1)	BF	25% MVC Extension	Ant/Ag	18.63	18.12	No
Kellis et al., (1999)†	M	9(12.6±0.5)	9(23.1±2.1)	VL	CON - 30°/s Flexion	Ant/Ag	12.2±2.2	16.5±7.0	No$^{\#}$
Kellis et al., (1999)†	M	9(12.6±0.5)	9(23.1±2.1)	VL	ECC - 30°/s Flexion	Ant/Ag	12.2±4.0	12.2±7.2	No
Kellis et al., (1999)†	M	9(12.6±0.5)	9(23.1±2.1)	BF	CON - 30°/s Extension	Ant/Ag	20.0±12.0	19.1±12.0	No
Kellis et al., (1999)†	M	9(12.6±0.5)	9(23.1±2.1)	BF	ECC - 30°/s Extension	Ant/Ag	14.5±4.0	13.5±9.0	No
Kellis et al., (1999)†	F	9(12.7±0.5)	9(23.7±3.1)	VL	CON - 30°/s Flexion	Ant/Ag	15.1±7.0	17.6±7.5	No$^{\#}$
Kellis et al., (1999)†	F	9(12.7±0.5)	9(23.7±3.1)	VL	ECC - 30°/s Flexion	Ant/Ag	14.0±15.5	15.5±5.0	No$^{\#}$
Kellis et al., (1999)†	F	9(12.7±0.5)	9(23.7±3.1)	BF	CON - 30°/s Extension	Ant/Ag	12.3±5.5	19.5±7.5	No$^{\#}$
Kellis et al., (1999)†	F	9(12.7±0.5)	9(23.7±3.1)	BF	ECC - 30°/s Extension	Ant/Ag	10.5±3.0	16.2±6.5	No$^{\#}$
Kochanowicz et al., (2018) – gymnasts†	M	20(8.5)	12(21.5)	AD	Maximal Iso Extension	Ant/Ag	4.37±1.72	5.56±3.94	No$^{\#}$
Kochanowicz et al., (2018)†	M	20(8.5)	15(21.5)	BB	Maximal Iso Extension	Ant/Ag	15.46±7.03	12.17±8.16	No
Kochanowicz et al., (2018)†	M	20(8.5)	15(21.5)	AD	Maximal Iso Extension	Ant/Ag	4.57±2.62	3.19±0.87	No
Lambertz et al., (2003)†	M/F	5(7)	6(20.8±1.6)δ	TA	25 and 75% MVC PF	Sum of TA/TS at 25% and TA/TS at 75%	2.3±0.5δ	1.18±0.2δ	No
Lambertz et al., (2003)†	M/F	7(8)	6(20.8±1.6)δ	TA	25 and 75% MVC PF	Sum of TA/TS at 25% and TA/TS at 75%	1.9±0.3δ	1.18±0.2δ	No
Lambertz et al., (2003)†	M/F	5(9)	6(20.8±1.6)δ	TA	25 and 75% MVC PF	Sum of TA/TS at 25% and TA/TS at 75%	1.6±0.2δ	1.18±0.2δ	No
Lambertz et al., (2003)†	M/F	11(10)	6(20.8±1.6)δ	TA	25 and 75% MVC PF	Sum of TA/TS at 25% and TA/TS at 75%	1.6±0.3δ	1.18±0.2δ	No
Morse et al., (2008)	M	11(10.9±0.3)	12(25.3±4.4)	TA	Maximal Iso PF	Ant/Ag	11.8±6.7	13.5±5.9	No$^{\#}$
O'Brien et al., (2009)	M	10(8.9±0.7)	10(28.2±3.6)	BF	Maximal Iso Flexion	Ant/Ag	8.4±5.5	6.6±3.1	No
O'Brien et al., (2009)	F	10 (9.3±0.8)	10(27.4±4.2)	BF	Maximal Iso Flexion	Ant/Ag	7.6±4.3	8.3±4.8	No$^{\#}$
O'Brien et al., (2010)	M	10(8.9±0.7)	10(28.2±3.6)	BF	Maximal Iso Flexion	Ant/Ag	7.78	5.93	No

O'Brien et al., (2010)	F	10(9.3±0.8)	10(27.4±4.2)	BF	Maximal Iso Flexion	Ant/Ag	8.53	12.97	No[#]
Grosset et al.,(2008)†	M/F	6(7)	9(21)	TA	25%MVC	TA/TA at 25%÷TA/TS at MVC	2.25±0.25δ	1.05±0.15δ	Yes
Grosset et al.,(2008)†	M/F	7(8)	9(21)	TA	25%MVC	TA/TA at 25%÷TA/TS at MVC	1.7±0.2δ	1.05±0.15δ	Yes
Grosset et al.,(2008)†	M/F	8(9)	9(21)	TA	25%MVC	TA/TA at 25%÷TA/TS at MVC	1.5±0.15δ	1.05±0.15δ	Yes
Grosset et al.,(2008)†	M/F	11(10)	9(21)	TA	25%MVC	TA/TA at 25%÷TA/TS at MVC	1.53±0.2δ	1.05±0.15δ	Yes
Grosset et al.,(2008)†	M/F	5(11)	9(21)	TA	25%MVC	TA/TA at 25%÷TA/TS at MVC	1.4±0.2δ	1.05±0.15δ	Yes
Hassani et al., (2009)	M	25(9.8±1.1)	25(29.6±0.5)	BF	Maximal Iso Extension at 5° ROM	Ant/Ag	32.8±11	23.6±13.4	Yes
Hassani et al., (2009)	M	25(9.8±1.1)	25(29.6±0.5)	BF	Maximal Iso Extension at 50° ROM	Ant/Ag	27.6±11	20.6±9.1	Yes
Hassani et al., (2009)	M	25(9.8±1.1)	25(29.6±0.5)	BF	Maximal Iso Extension at 95° ROM	Ant/Ag	38.1±12.5	35.3±10.8	Yes
Kochanowicz et al., (2018) – gymnasts†	M	20(8.5)	12(21.5)	TB	Maximal Iso Flexion	Ant/Ag	11.78±4.56	6.29±2.6	Yes
Kochanowicz et al., (2018) – gymnasts†	M	20(8.5)	12(21.5)	BB	Maximal Iso Extension	Ant/Ag	14.42±7.03	3.59±1.51	Yes
Kochanowicz et al., (2018) – gymnasts†	M	20(8.5)	12(21.5)	LD	Maximal Iso Flexion	Ant/Ag	4.37±1.72	17.84±9.55	Yes[#]
Kochanowicz et al., (2018)†	M	20(8.5)	15(21.5)	TB	Maximal Iso Flexion	Ant/Ag	17.68±6.91	12.68±4.63	Yes
Kochanowicz et al., (2018)†	M	20(8.5)	15(21.5)	LD	Maximal Iso Flexion	Ant/Ag	14.61±10.67	29.63±15.03	Yes[#]

AD – Anterior Deltoid
Ant/Ag – Antagonist activation over muscles activation as an agonist
BB – Biceps Brachii
BF – Biceps Femoris
CON – Concentric muscle contraction
ECC – Eccentric muscle contraction
F- Female
Iso – Isometric contraction
LD – Latissimus Dorsi
M - Male
VL – Vastus Lateralis
TA – Tibialis Anterior
TB – Triceps Brachii

ROM – Range of motion
PF – Plantar Flexion
† - Data extracted from figure
#- Indicates greater coactivation in adults compared with children
δ - indicates standard error

Table 2. Multi-Joint – Dynamic Jump Comparisons. Values are mean±SD, unless otherwise indicated

Study	Sex	Participants n (age, year)			Muscles studied	Contraction task	Calculation method	Coactivation (%)			Statistically significant
		Children 1	Children 2	Adults				Children 1	Children 2	Adults	
Lazardis et al., (2013)†	M	12(9.8±0.6)		12(25.5±2.7)	BF/VL	Squat Jump – Propulsive Phase	BF/VL	1.4±0.3		1.2±0.2	No
Lazardis et al., (2013)†	M	12(9.8±0.6)		12(25.5±2.7)	BF/VL	CMJ - Breaking Phase	BF/VL	1.2±0.4		0.9±0.3	No
Lazardis et al., (2013)†	M	12(9.8±0.6)		12(25.5±2.7)	BF/VL	DJ - 20cm - Pre-activation	BF/VL	1.3±0.5		1.1±0.4	No
Lazardis et al., (2013)†	M	12(9.8±0.6)		12(25.5±2.7)	BF/VL	DJ - 40cm - Propulsive Phase	BF/VL	1.25±0.2		1.0±0.35	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	BF/VL	Maximal Bilateral Hop – 0-30ms post-contact	BF/VL	0.48±0.49	0.43±0.43	0.28±0.25	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	BF/VL	Maximal Bilateral Hop – 31-60ms post-contact	BF/VL	0.72±0.47	1.01±1.23	0.74±0.72	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	BF/VL	Maximal Bilateral Hop – 61-90ms post-contact	BF/VL	0.56±0.47	0.57±0.58	0.38±0.33	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	BF/VL	Maximal Bilateral Hop – 91-120ms post-contact	BF/VL	0.67±0.45	0.58±0.53	0.44±0.39	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	TA/SOL	Maximal Bilateral Hop – 0-30ms post-contact	TA/SOL	0.62±0.8	0.31±0.07	0.28±0.07	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	TA/SOL	Maximal Bilateral Hop – 31-60ms post-contact	TA/SOL	0.69±0.87	0.39±0.14	0.29±0.08	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	TA/SOL	Maximal Bilateral Hop – 61-90ms post-contact	TA/SOL	0.65±0.83	0.33±0.09	0.28±0.06	No
Lloyd et al., (2012)	M	11(9.4±0.3)	11(12.7±0.3)	10(15.9±.3)	TA/SOL	Maximal Bilateral Hop – 91-120ms post-contact	TA/SOL	1.22±2.40	0.47±0.16	0.36±0.13	No
Oliver et al., (2010)†	M	11(11.5)		10(24.5)	BF/VL	Hopping Task – 1.5 Hz	BF/VL	0.34±0.39		0.21±0.12	No
Oliver et al., (2010)†	M	11(11.5)		10(24.5)	BF/VL	Hopping Task – 30 Hz	BF/VL	0.31±0.29		0.19±0.12	No
Oliver et al., (2010)†	M	11(11.5)		10(24.5)	BF/VL	Hopping Task - Preferred	BF/VL	0.36±0.28		0.56±0.33	No[#]
Oliver et al., (2010)†	M	11(11.5)		10(24.5)	TA/SOL	Hopping Task – 1.5 Hz	TA/SOL	1.55±0.83		1.27±0.8	No

Oliver et al., (2010)†	M	11(11.5)	10(24.5)	TA/SOL	Hopping Task – 30 Hz	TA/SOL	1.15±0.87	0.78±0.71	No
Oliver et al., (2010)†	M	11(11.5)	10(24.5)	TA/SOL	Hopping Task - Preferred	TA/SOL	0.43±0.19	0.56±0.58	No[#]
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/BF	CMJ - ECC	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	4.64	4.95	No[#]
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/BF	CMJ - CON	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	10.26	10.57	No[#]
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/ BF	DJ-30cm -30pre	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	1.29	1.12	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/ BF	DJ-30cm - 30con	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	8.76	8.03	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/ BF	DJLand – Pre-landing 30cm children/ 60cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	1.51	1.05	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/BF	DJland – CON 30cm children/ 60cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	4.86	2.3	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/ BF	DJland- Pre-landing 60cm children/ 90cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	1.93	1.05	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VL/ BF	DJland – CON 30cm children/ 90cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	5.45	1.59	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	CMJ - ECC	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	1.59	1.77	No[#]
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	CMJ - CON	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	2.56	2.73	No[#]
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	DJ-30cm -30pre	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	.9	.84	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	DJ-30cm - 30con	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	3.24	3.12	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	DJLand – Pre-landing 30cm children/ 60cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	.92	.58	No

Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	VM/ SEM	DJland- Pre-landing 60cm children/ 90cm adults	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	1.17	1.25	No#
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	CMJ - ECC	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	3.08	2.26	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	CMJ - CON	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	4.53	2.21	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJ-30cm -30pre	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	1.37	0.64	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJ-30cm - 30con	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	4.35	1.88	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJLand – Pre-landing 30cm children/60cm adults	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	1.33	0.7	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJland – CON 30cm children/ 60cm adults	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	2.57	2.32	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJland- Pre-landing 60cm children/ 90cm adults	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	2.16	0.91	No
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	TA/SOL	DJland –CON 30cm children/ 90cm adults	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG} \times (LesserEMG$	3.85	2.61	No
Russell et al., (2007)	M/F	M 14(9.6±1.0) F 14(9.3±0.9)	M 13(23.6±3.4) F 14(24.2±2.3)	VM/SEM	CMJ - 100ms after contact	Flexors/Extensors	100.99±2.56 δ	86.06±2.61δ	No
Russell et al., (2007)	M/F	M 14(9.6±1.0) F 14(9.3±0.9)	M 13(23.6±3.4) F 14(24.2±2.3)	VM/SEM	CMJ-100ms after contact to maximum knee flexion	Flexors/Extensors	124.17±8.28 δ	118.85±5.91 δ	No
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)	21(15.7±1.1)	VL/VM/BF/Med Gas	Double leg jump - Pre Contact	$\frac{LesserEMG}{Greater\ EMG + Greater\ EMG)} \times (LesserEMG$	0.14±0δ	0.11±0.03δ	No
Croce et al., (2004)	M	15(9.6±1.0)	14(23.6±3.2)	VM/BF	Double leg jump at 50% of max jump height – Pre-activation	VM/BF	288.2±111.3	652.6±538.8	Yes#
Croce et al., (2004)	M	15(9.6±1.0)	14(23.6±3.2)	VM/BF	Double leg jump at 50% of max jump	VM/BF	106.0±21.7	81.1±17.7	Yes

					height – Post activation (reflexive)				
Croce et al., (2004)	M	15(9.6±1.0)	14(23.6±3.2)	VM/BF	Double leg jump at 50% of max jump height – Max knee flexion	VM/BF	108.7±23.3	95.2±35.0	Yes
Croce et al., (2004)	F	15(9.19±1.0)	14(24.2±2.3)	VM/BF	Double leg jump at 50% of max jump height – Pre-activation	VM/BF	313.4±122.4	625.1±353.8	Yes#
Croce et al., (2004)	F	15(9.19±1.0)	14(24.2±2.3)	VM/BF	Double leg jump at 50% of max jump height – Post activation (reflexive)	VM/BF	103.5±18.8	80.3±15.4	Yes
Croce et al., (2004)	F	15(9.19±1.0)	14(24.2±2.3)	VM/BF	Double leg jump at 50% of max jump height – Max knee flexion	VM/BF	101.5±15.4	89.1±17.7	Yes
Lazardis et al., (2010)	M	12(9.8±0.6)	12(25.5±2.7)	Med GAS/ SOL/TA	Drop jump – 20cm – Breaking Phase	TA/SM+SOL	0.82±0.36	0.46±0.2	Yes
Lazardis et al., (2010)	M	12(9.8±0.6)	12(25.5±2.7)	Med GAS/ SOL/TA	Drop jump – 20cm – Propulsion Phase	TA/SM+SOL	0.3±0.13	0.2±0.07	Yes
Lazardis et al., (2013)†	M	12(9.8±0.6)	12(25.5±2.7)	BF/VL	CMJ – Propulsive Phase	BF/VL	1.3±0.3	1.1±0.2	Yes
Lazardis et al., (2013)†	M	12(9.8±0.6)	12(25.5±2.7)	BF/VL	DJ- 20cm – Propulsive Phase	BF/VL	1.2±0.1	1±0.1	Yes
Lazardis et al., (2013)†	M	12(9.8±0.6)	12(25.5±2.7)	BF/VL	DJ- 20cm – Breaking Phase	BF/VL	1.1±0.2	0.9	Yes
Lazardis et al., (2013)†	M	12(9.8±0.6)	12(25.5±2.7)	BF/VL	DJ- 40cm – Pre-Activation Phase	BF/VL	1.4±0.2	1.1±0.3	Yes
Lazardis et al., (2013)†	M	12(9.8±0.6)	12(25.5±2.7)	BF/VL	DJ- 40cm – Breaking Phase	BF/VL	1.3±0.5	0.9±0.2	Yes
Raffalt et al., (2017)†	M	10(11.5±1.8)	10(26.3±5.0)	RF/VL/ SEM	DJland – CON phase 30cm children/60cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	2.16	1.46	Yes
Raffalt et al., (2017) †	M	10(11.5±1.8)	10(26.3±5.0)	RF/VL/ SEM	DJland – CON phase 30cm children/90cm adults	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG$	2.92	1.46	Yes

Russell et al., (2007)	M/F	M 14(9.6±1.0) F 14(9.3±0.9)	M 13(23.6±3.4) F 14(24.2±2.3)	VM/SEM/BF	50% of max jump height- 100ms before contact	Flexors/Extensors	308.3±51.0	619.0±52.0	Yes$^{\#}$
Russell et al., (2007)	M/F	M 14(9.6±1.0) F 14(9.3±0.9)	M 13(23.6±3.4) F 14(24.2±2.3)	VM/SEM/BF	Pooled coactivation ratio from all jump phases	Flexors/Extensors	177.8±126.4	272.9±333.8	Yes$^{\#}$
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)	21(15.7±1.1)	VL/VM/BF/Med Gas	Double Leg Jump Weight Acceptance	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.53±0.04δ	0.31±0.03δ	Yes
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)	21(15.7±1.1)	VL/VM/BF/Med Gas	Single-Leg Jump Pre-Contact	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.35±0.02δ	0.27±0.03δ	Yes
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)	21(15.7±1.1)	VL/VM/BF/Med Gas	Single – Leg Jump Weight Acceptance	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.74±0.03δ	0.51±0.04δ	Yes

BF – Biceps Femoris
CMJ – Countermovement jump
CON – Concentric muscle contraction
DJ – Drop jump
ECC – Eccentric muscle contraction
F – Female
GAS – Gastrocnemius
M – Male
$\tilde{X}$ – Median of the data was extracted
Med- Medial
VL – Vastus Lateralis
VM – Vastus Medialis
SEM – Semitendinosus
SOL – Soleus
TA – Tibialis Anterior
PF – Plantar Flexion
† - Data extracted from figure
$^{\#}$ - Indicates greater coactivation in adults compared with children
δ - indicates standard error

Table 3. Multi-Joint – Dynamic Gait/Other Comparisons. Values are mean±SD, unless otherwise indicated

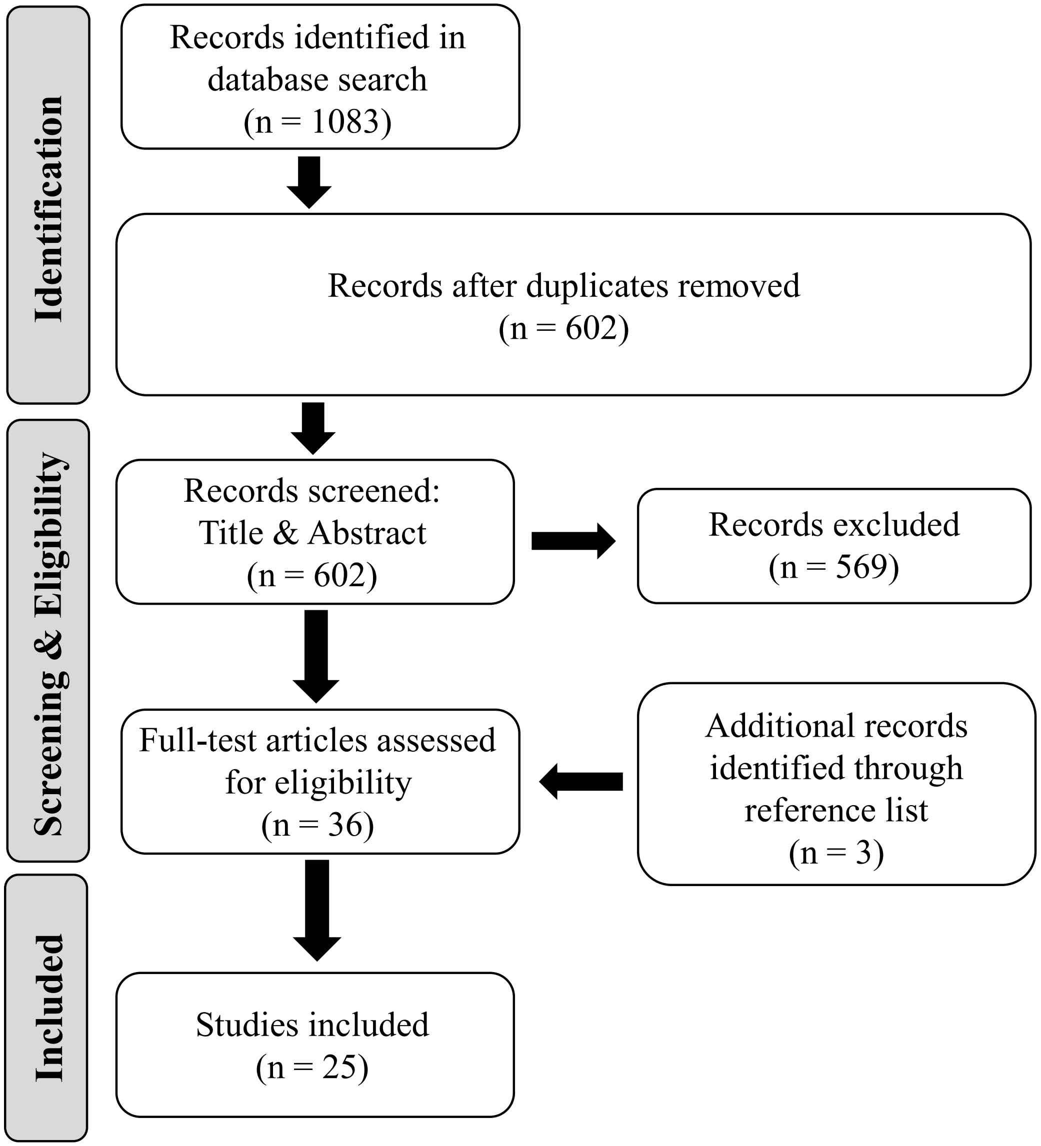
Study	**Sex**	**Participants n (age, year)**			**Muscle studied**	**Contraction task**	**Calculation method**	**Coactivation (%)**			**Statistically significant**
		Children 1	**Children 2**	**Adults/ Adolescences**				**Children 1**	**Children 2**	**Adults/ Adolescences**	
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Preferred Speed - Unweighted	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	54.4±6.0		50.7±9.0	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Preferred Speed - 20%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	48.7±4.0		44.8±8.9	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Preferred Speed - 40%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	47.4±4.0		48.6±7.6	No*
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Preferred Speed - 60%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	37.6±9.8		47.0±7.7	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Preferred Speed - 80%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	38.1±13.0		39.7±12.2	No*
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Gait Froude Number Speed – Unweighted	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	52.1±5.1		49.5±8.9	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Gait Froude Number Speed – 20%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	47.5±10.1		48.9±9.5	No*
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Gait Froude Number Speed – 40%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	38.0±12.2		39.4±11.7	No*
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Gait Froude Number Speed – 60%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	38.8±10.8		29.4±15.2	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	VL/BF	Gait Froude Number Speed – 80%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	36.8±12.1		27.6±12.1	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Walking 25-29%VO2max	Area of overlap of VL and HAM	6.54±1.10	6.24±1.65	4.53±1.35	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Walking 31-38%VO2max	Area of overlap of VL and HAM	7.27±1.16	9.60±3.67	6.85±1.71	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Running 59-62%VO2max	Area of overlap of VL and HAM	12.97±1.47	9.17±1.71	10.40±2.20	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Walking 25-29%VO2max	Area of overlap of TA and SOL	9.86±1.30	10.17±2.14	10.09±1.53	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Walking 31-38%VO2max	Area of overlap of TA and SOL	13.69±1.61	13.38±3.82	11.31±1.45	No
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Running 59-62%VO2max	Area of overlap of TA and SOL	18.04±1.91	12.38±1.45	14.52±1.99	No
Frost et al., (2002)	M/F	10(7.5)	10(11)		VL/HAM	Walking 1.34 m/s	Area of overlap of VL and HAM	7.32	5.64		No
Frost et al., (2002)	M/F	10(7.5)	10(11)		VL/HAM	Running 2.19 m/s	Area of overlap of VL and HAM	13.59	11.35		No
Frost et al., (2002)	M/F		10(11)	10(15.5)	VL/HAM	Walking 1.56 m/s	Area of overlap of VL and HAM	7.04	4.56		No
Frost et al., (2002)	M/F		10(11)	10(15.5)	VL/HAM	Running 2.32 m/s	Area of overlap of VL and HAM	14.28	10.46		No

Frost et al., (2002)	M/F		10(11)	10(15.5)	TA/SOL	Walking 1.56 m/s	Area of overlap of TA and SOL	10.53	10.00		No
Frost et al., (2002)	M/F		10(11)	10(15.5)	TA/SOL	Running 2.32 m/s	Area of overlap of TA and SOL	13.62	14.52		No*
Frost et al., (2002)	M/F		10(11)	10(15.5)	TA/SOL	Running 2.46 m/s	Area of overlap of TA and SOL	13.97	13.51		No
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)		21(15.7±1.1)	VL/VM/BF/Med Gas	Pre-Planned Cut Pre-Contact	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.21±0.03δ		0.22±0.01δ	No
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)		21(15.7±1.1)	VL/VM/BF/Med Gas	Unanticipated Cut Pre-Contact	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.17±0δ		0.19±0.01δ	No*
Quinzi et al., (2015)†	M	6(15.5±1.0)		6(27.7±2.6)	VL/BF	Roundhouse Kick – Maximal Speed - Flexion	Ant/Ag	50.24±25.27		46.25±14.55	No
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Preferred Speed - Unweighted	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	38.6±8.9		25.6±5.0	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Preferred Speed - 20%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	35.4±7.0		25.2±4.6	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Preferred Speed - 40%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	35.8±6.7		24.9±6.1	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Preferred Speed - 60%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	36.5±5.9		24.0±3.7	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Preferred Speed - 80%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	35.5±6.4		26.9±8.6	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Gait Froude Number Speed – Unweighted	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	34.3±4.8		26.1±5.2	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Gait Froude Number Speed – 20%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	37.8±7.3		27.1±9.6	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Gait Froude Number Speed – 40%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	35.9±7.4		23.1±4.7	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Gait Froude Number Speed – 60%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	38.9±6.9		24.6±7.7	Yes
Deffeyes et al., (2012)	M/F	9(13.2±2.2)		10(25.2±4.3)	TA/Lat GAS	Gait Froude Number Speed – 80%BW	$100\,x\,\frac{2 \times overlapAB}{Total\ A + Total}$	35.9±4.7		21.8±4.5	Yes
Kurz et al., (2018)	M/F	19(9.7±0.5)		30(23.3±1.5)	TA/SOL	Quiet Standing	Degree of simultaneous activity	0.78±0.15		0.55±0.15	Yes
Quinzi et al., (2015)†	M	6(15.5±1.0)		6(27.7±2.6)	VL/BF	Roundhouse Kick – Maximal Speed - Extension	Ant/Ag	30.48±21.75		61.01±14.01	Yes*
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Running 56-64%VO2max	Area of overlap of VL and HAM	13.70±1.35	11.19±1.22	8.07±1.34	Yes – children 1 & adolescence

Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Running 65-68%VO2max	Area of overlap of VL and HAM	14.43±1.77	14.07±1.90	7.65±1.83	Yes – children 1/2 & adolescence
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	VL/HAM	Running 68-72%VO2max	Area of overlap of VL and HAM	13.82±1.83	14.25±1.77	7.83±1.53	Yes – children 1/2 & adolescence
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Running 56-64%VO2max	Area of overlap of TA and SOL	21.10±2.75	13.76±1.45	13.45±2.52	Yes – children 1 & children 2/adolescence
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Running 65-68%VO2max	Area of overlap of TA and SOL	19.34±1.83	13.61±1.30	12.16±1.83	Yes – children 1/2 & adolescence
Frost et al., (1997)†	M/F	10(7.5)	10(11)	10(15.5)	TA/SOL	Running 68-72%VO2max	Area of overlap of TA and SOL	19.34±1.83	13.69±1.68	13.76±1.99	Yes – children 1 & children 2/adolescence
Frost et al., (2002)	M/F	10(7.5)	10(11)		VL/HAM	Running 2.06 m/s	Area of overlap of VL and HAM	14.45	9.37		Yes
Frost et al., (2002)	M/F		10(11)	10(15.5)	VL/HAM	Running 2.46 m/s	Area of overlap of VL and HAM	14.81	8.18		Yes
Frost et al., (2002)	M/F	10(7.5)	10(11)		TA/SOL	Walking 1.34 m/s	Area of overlap of TA and SOL	13.87	8.94		Yes
Frost et al., (2002)	M/F	10(7.5)	10(11)		TA/SOL	Running 2.06 m/s	Area of overlap of TA and SOL	19.40	12.56		Yes
Frost et al., (2002)	M/F	10(7.5)	10(11)		TA/SOL	Running 2.19 m/s	Area of overlap of TA and SOL	19.66	13.78		Yes
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)		21(15.7±1.1)	VL/VM/BF/Med Gas	Pre-Planned Cut Weight Acceptance	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.65±0.05δ		0.50±0.05δ	Yes
Thompson-Kolesar et al., (2018)†	F	23(11.2±0.6)		21(15.7±1.1)	VL/VM/BF/Med Gas	Unanticipated Cut Weight Acceptance	$\frac{LesserEMG}{Greater\ EMG} \times (LesserEMG + Greater\ EMG)$	0.65±0.04δ		0.47±0.04δ	Yes

BF – Biceps Femoris
BW – Body Weight
Children1 – Younger group of children
Children1 – Older group of children
F – Female

HAM – Hamstring muscle group
GAS – Gastrocnemius
M – Male
Med – Medial
VL – Vastus Lateralis
SEM – Semitendinosus
SOL – Soleus
TA – Tibialis Anterior
PF – Plantar Flexion
† - Data extracted from figure
* Indicates greater coactivation in adults compared with children
δ - indicates standard error


Identification
Screening & Eligibility
Included
Records identified in database search (n = 1083)
Records after duplicates removed (n = 602)
Records screened: Title & Abstract (n = 602)
Records excluded (n = 569)
Full-test articles assessed for eligibility (n = 36)
Additional records identified through reference list (n = 3)
Studies included (n = 25)