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The effects of age and skill level on knee musculature co-contraction during functional activities: a systematic review

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Abstract

Objectives—To systematically review the current literature that relates the effects of age and skill level to motor control patterns of knee musculature co-contraction during functional movements.

Methods—A search of electronic databases was performed with the search terms specifying co-contraction (cocontract*, co-contract*, coactive* or co-activ*). The search was focused on the effects age and/or skill level and were limited by the keywords of age or skill level (skill*) or experience (experi*).

Results—The search yielded a total of six peer-reviewed manuscripts that met the search criteria and were included in the review.

Conclusions—The relationship between adequate dynamic joint stability and efficient movement patterns are complex. Co-contraction related to age and skill development varies among studies due to technical and practical considerations. Adequate antagonistic co-contraction of hamstring musculature seems to be a component of all functional movements, possibly maintain dynamic knee stability and protect against excessive joint loads. Future investigations that further delineate the appropriate lower extremity agonist and antagonist relationships during dynamic tasks may help elucidate injury risk mechanisms in specific populations.

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The development of sports-related skills requires - complex coordination between the agonistic and antagonistic muscles at a joint to maximise the degrees of freedom and force output with the required dynamic restraints to maintain the required local joint stability.[1] During maturation and skill development, inhibition of antagonist muscle groups is thought to be progressively learned until an efficient movement pattern is obtained.[2] A classic motor learning theory contends that excessive antagonistic contribution during dynamic tasks may decrease the system's "degrees of freedom" during initial acquisition of a new skill.[134] Accordingly, the degrees of freedom are gradually increased and optimised in order to execute the task in the most efficient manner by the skilled performer.[34] Previous investigations have evaluated this relationship between agonistic and antagonistic muscles systems in attempts to define optimum motor control and learning patterns in numerous types of movements in various populations.[156]

Muscular co-contraction is operationally defined as activation of both the agonist and antagonist muscle groups crossing the same joint.[7] Mechanically, increased activation levels of the antagonist muscle group results in greater joint stiffness, reduced agonist force output and reduced net joint moment.[7] During activities that require maximum performance (eg the push-off phase of a jump) or throughout the entire stretch shortening cycle, inhibition of antagonist muscles would often be considered an efficient adaptation. If antagonist muscle forces increase, more work is required and decreased efficiency results for any given movement. Thus when applying the theoretical model of motor performance, without consideration of the joint stability required to maintain the integrity of the joint, decreased co-contraction would be directly related to increased power output at a joint.

However, during dynamic human movement, co-contraction is a potential motor control strategy used to dynamically stabilise and protect a joint. Joint stability through co-contraction may be necessary when the joint experiences high distraction or shear forces and/or when the passive structures are compromised. For example, hamstring activation can decrease the load on the passive restraints of the knee,[8] increase the knee-joint compression force and stabilise the knee from external varus/valgus load.[9] A panel of experts suggests that female athletes, who are at a higher risk of anterior cruciate ligament (ACL) injury than are male athletes,[10] should focus on hamstring-strengthening exercises[11] and appropriate dynamic co-contraction (without limiting joint motion). Increased strength and recruitment of the hamstring musculature may help to decrease the coronal plane rotations and anterior shear forces on the ACL.[9] Female athletes exhibit increased coronal plane motion and moments during a variety of athletic manoeuvres compared with male athletes.[12-17] Decreased ability to control external coronal plane loads may be a symptom of decreased ability to recruit the hamstring musculature, especially in response to increased quadriceps strength at high velocities.[18] Decreased co-contraction and dynamic stabilisation of the knee joint in response to excessive coronal plane loads may underlie the increased risk of ACL injury in female athletes.[19]

Co-contraction levels are high during normal dynamic joint loading movements such as landing.[20] Considering that there is a potential conflict between joint stability and movement efficiency, important insights may be gained by comparing co-contraction levels among various movement tasks in relation to the mechanistic effects of age and skill development.

The purpose of the current report was to critically review the current literature that relates the effects of age and skill level on motor control patterns of knee musculature co-contraction during functional movements.

METHODS

A search of electronic databases, MEDLINE (1966– October 2006) and CINAHL (1982– June 2007), was performed with the search terms specifying co-contraction (cocontract*, co-contract*, coactive* or co-activ*). The search was focused on the effects age and/or skill level and were limited by the keywords of age or skill level (skill*) or experience (experi*). An article was included in the review if it was a randomised controlled trial or cohort study and investigated co-contraction (index or ratio) with electromyographical analyses during functional activity. Articles that did not perform investigations on normal or athletic populations (i.e. osteoarthritis and elderly) were excluded. Abstracts and unpublished studies were also excluded.

RESULTS

Six articles[6,21-25] that presented knee muscular co-contraction patterns in relation to age or skill level were identified. Each article is briefly described by publication date (table 1). Interpretations and possible limitations of each study are presented in detail in the discussion.

Frost *et al*

The stated purpose of this study[22] was to assess co-contraction of three different age groups of children during walking and jogging and to compare the magnitude of co-contraction among them. The investigation evaluated a total of 30 total healthy, active subjects with 10 subjects in each age group (7–8, 10–12 and 15–16 years). Five different treadmill speeds (two walking and three jogging) were used for each age group, with one walking and two jogging speeds in common between adjacent age groups. Surface electromyography (EMG) electrodes (Ag/AgCl) were placed on the vastus lateralis and “middle of the hamstring group” (no specific muscle was identified in the paper) with an interelectrode distance of 4 cm. Raw EMG was first normalised to the maximum value obtained during either the treadmill trials or maximum voluntary contraction (MVC) trials. A co-contraction index, dimensionless value, was calculated based on overlaying the linear envelopes of the vastus lateralis and hamstring, calculating the area of overlap and dividing by the number of data points. Frost *et al*.[22] found when comparing the running speeds at the same relative metabolic intensity (% VO_{2max}) the co-contraction index was higher in younger compared with older age groups. They concluded that co-contraction was an important component of age-related differences in VO_2, which was possibly used to enhance joint stability at the younger age.

Croce *et al*

This study[24] examined the differences between prepubescent and postpubescent male and female subjects. The authors stated that different stabilisation patterns might be a causative factor related to ACL injuries. Two groups of subjects were studied based on age and were classified as prepubescent (7–10-year-old girls, and 8–11-year-old boys) or post-pubescent (19–29-year-old men and women). A two-foot vertical jump (50% of maximum) and landing was analysed with the subject landing with the dominant foot on a force platform. EMG surface electrodes (Ag/AgCl, pre-gelled) were placed on the biceps femoris, semimembranosus/semitendinosus and vastus medialis. The electrodes were located 2.5 cm apart, parallel to the muscle fibres and over the midline between the motor end plate and tendon. The data from the hamstring muscle sites were averaged. Mean amplitude root mean square (RMS) was calculated at three different time intervals during the trials (100 ms before contact, 100 ms after contact and from contact to maximum knee flexion). The EMG signal was normalised to the highest signal during the landing phase of each trial. Co-contraction ratio was calculated by dividing hamstring by quadricep EMG activity. Co-contraction ratio was higher in the postpubescent subjects before landing; however, after landing, the co-contraction ratio was higher in prepubescent subjects. No gender differences were found in co-contraction during the vertical jump. The authors concluded that post-pubescent subjects rely more on hamstring activation before landing (preactivation), whereas prepubescent subjects rely more on hamstring activation during landing (reflexive activation pattern). This would seem to relate to a motor learning strategy throughout skill development of preactivation to stabilise the joint before the high ground reaction forces and joint load, which exist during landing.

Hamstra-Wright *et al*

The purposes of this study[6] were to assess dynamic neuromuscular restraint differences between high-skilled and low-skilled prepubescent children and to determine the contributions of sport experience and physical characteristics to motor skill. The authors hypothesised that high-skilled and male subjects would have greater co-contraction (hamstrings and quadriceps) than low skilled and female subjects. In total, 36 prepubescent children were enrolled in this study (19 girls and 17 boys). High skill and low skill were determined based on performance of battery of 12 fundamental motor skills on the Test of Gross Motor Development, second edition (TGMD-2). Subjects above the overall mean were classified as high-skilled, while subjects below the mean were classified as low-skilled. Surface EMG electrodes (bipolar Ag/AgCl) were placed on the vastus medialis and medial hamstring. EMG was normalised to the highest activity during each trial (150 ms before ground contact to 250 ms after, inclusive). Preparatory co-contraction was determined as the medial hamstring area divided by the vastus medialis area 150 ms before ground contact during a drop jump (24 cm). Vertical leg stiffness was also determined during the drop jumps based on a simple spring-mass model from the vertical ground reaction force measures. Low-skilled subjects had significantly greater (48%) preparatory co-contraction during the drop jump compared with high-skilled subjects. No differences were found in vertical leg stiffness between skill or gender groups. The authors concluded, based on the higher co-contraction in low-skilled subjects, that, in addition to the lack of gender differences, skill level affects neuromuscular control. They further suggest that girls may develop risk factors that predispose them to knee injuries between pre-puberty and post-puberty. The authors state that this was an “unrefined motor skill” that may compromise knee joint stability. This conclusion is in direct contrast to the study hypothesis that high-skilled athletes would exhibit greater preparatory co-contraction.

da Fonseca *et al*

This study[21] compared muscular co-contraction levels among male and female athletic and sedentary subjects during walking and landing from a jump (30 cm). They hypothesised that females (athletic and sedentary) would have lower co-contraction levels than males. The hypothesis was based on both the higher ACL injury rates in females and the possible joint protective mechanism that co-contraction may have due to increased joint stiffness. Nine subjects in each group participated, with their activity level classified based on the Cincinnati Knee Rating Scale (level I, participate in sports activities 4–7 days a week; level IV, do not participate in any sports activities). Surface EMG electrodes (bipolar Ag/AgCl) were placed over the vastus lateralis and biceps femoris with co-contraction index calculated similar to Frost *et al*[22] during both walking and landing from a jump. EMG was filtered with a bandpass filter (10 and 500 Hz) and normalised to MVC collected from a dynamometer. Co-contraction index was only calculated for the 150 ms time period before initial contact. There were no differences in preparatory co-contraction index during landing movements between genders or activity levels. However, during walking, the sedentary females had higher co-contraction levels compared with athletic females. The authors suggest that sedentary women may compensate for weakness with higher co-contraction levels to generate appropriate joint stability.

Sigward and Powers

This study[23] evaluated the effect of soccer experience on knee kinematics, kinetics and muscle activation patterns during side step cuts. One hypothesis of this study was that novice female athletes would exhibit increased quadriceps activation and decreased hamstring activation. Thirty young female athletes (14–16 years old) were classified as experienced (n = 15) or novice (n = 15) based on years of experience playing soccer. Surface EMG electrodes were placed on the vastus lateralis, biceps femoris and semimembranousus. EMG was filtered with a band-pass Butterworth filter (20–500 Hz) and a 60 Hz notch filter. The data were processed with RMS smoothing (75 ms window), and normalised to maximum voluntary isometric contraction collected before the cutting trials. Co-contraction was calculated, based on Besier *et al*,[26] by dividing the average hamstring activation by the average quadriceps activation during the initial 20% of the cutting manoeuvre stance phase (early deceleration). Knee joint kinematics and kinetics were also assessed during the same period. During early deceleration, the novice athletes had a significantly larger co-contraction index than the experienced athletes. However, the internal knee flexor moment was significantly increased in the experienced athletes compared with the novice athletes. There was also a negative correlation ($R = -0.32$) between years of experience and co-contraction ratio. The authors concluded that with experience, the side-step cutting (kinetics and muscle co-contraction) task is performed in a more at-risk pattern for a non-contact knee injury. The relationship between skill acquisition (increased co-contraction) and potential at-risk patterns (decreased co-contraction) is difficult to address in one study and should be investigated in conjunction with neuromuscular training programmes.

Russell *et al*

In a follow-up study[25] to another previously reviewed[24], Russel *et al* evaluated knee muscular activation differences in children and adults (male and female) during landing from a normal and perturbed vertical jump. The authors hypothesised that co-contraction gender differences would be evident with the addition of a perturbed landing in this study[25], in contrast to their previous work,[24] which found no gender differences during vertical jump landing. They also hypothesised that adults would exhibit a higher co-contraction ratio during the preparatory landing phase and that children would have higher co-contraction during the landing, as previously found.[24] EMG surface electrodes (Ag/AgCl pre-gelled) were placed on the biceps femoris, semimembranosus/semitendinosus and vastus medialis. The electrodes were located 2.5 cm apart, parallel to the muscle fibres and over the midline between the motor end plate and tendon. The data from the hamstring muscle sites were averaged. Mean amplitude RMS was calculated at three different time intervals during the trials (100 ms before contact, 100 ms after contact, and from contact to maximum knee flexion). The EMG signal was normalised to the highest signal during the landing phase of each trial. Co-contraction ratio was calculated by dividing hamstring by quadriceps EMG activity. A vertical jump was performed at 50% of the subject's maximum jump height during a normal condition (ball placed at subject's midline) and perturbed condition (ball offset 45.7 cm for adults and 30.5 cm for children from midline). The results of the study indicated that during the preparatory phase (100 ms before initial contact) the co-contraction ratio was higher in adults compared with children. This was explained by higher hamstring activity relative to quadriceps in adults before landing. No gender differences were found with or without the landing perturbation. The authors suggest that increased co-contraction during the preparatory phase is probably a learned feed-forward mechanism, as the children did not exhibit similar co-contraction levels.

DISCUSSION

Motor control mechanisms, which may be used for joint stability, involve feedback (reactive reflex) and feed-forward (preactivated) systems.[27] The electromechanical time delays that are inherent in the feedback mechanism limit the effectiveness of muscular joint protection during dynamic movements, but are better suited for maintaining posture and slower movements.[27] Feed-forward mechanisms involve preparatory activation by anticipation of the load or movement.[27] The preparatory activation can be learned and adjusted through integration of previous experiences of the skill or movement. As the individual becomes more experienced, inappropriate muscle co-contraction patterns (decreasing the systems "degrees of freedom") may be replaced by more coordinated muscle firing patterns for the development of appropriate dynamic joint stability and efficient movements. The results from the studies above do not fully support or refute this theory.

Of the six studies reviewed, the differences in methods and results make the synthesis of the author interpretations difficult. For example, three studies addressed co-contraction in landing movements, each with different results. Subjects classified as sedentary[21] did not have different preparatory co-contraction levels compared with active subjects. In another study, low-skilled children[6] had higher preparatory co-contraction levels compared with high-skilled children. In contrast, Croce *et al*[24] and Russell *et al*[25] found that during a landing, the preparatory co-contraction levels were higher in the older group than in the younger group. These conflicting results are probably due to differences in the tested population and in the methods used. Differences in EMG normalisation, calculation of co-contraction, electrode placement and signal processing are evident in these studies. A clear delineation of the effects of experience (age or skill level) on muscular co-contraction during a landing from a jump cannot be gleaned because of the differences among the studies. However, it would appear that during landings, co-contraction is generally considered an appropriate motor control strategy used to dynamically stabilise and protect the knee joint. It should also be noted that during landing, the role of hip flexion may complicate the interpretation of co-contraction at the knee based on the differences in uniarticular and biarticular muscles, which cross the knee joint.

Sigward and Powers[23] examined a side-step cutting manoeuvre in a group of female soccer players. They found higher co-contraction during the initial 20% of stance in a novice group than in the skilled group. The joint moment analysis did not appear to support the authors' interpretation of increased hamstring contraction in the novice group. A higher internal flexor moment generated during the initial 20% of stance in the skilled group would seem to relate to a net joint moment that is more towards flexor activation, in contrast to the presented co-contraction ratio (lower flexor/extensor ratio, co-contraction). The effects of normalisation or additional muscle contributions (ie gastrocnemius) to the net joint moment may explain the differences. The results of the only study in the review that examined a side-step cut would support the classic motor learning theory, which contends that excessive antagonistic contribution during dynamic tasks may decreases the system's "degrees of freedom" during initial acquisition of a new skill.[134] However, this may not be the most appropriate "learned" movement pattern in relation to a possible higher risk of injury.

Walking and running were investigated in two studies. Frost *et al*[22] found when running speeds were matched among three age groups (7–8, 10–12, 15–16 years) the younger children had higher co-contraction throughout the trial compared with the mature subjects. During walking, at matched treadmill speeds, the younger age groups also showed a trend toward higher co-contraction compared with the older age groups. When walking was examined in sedentary and active male and female subjects,[21] the only difference found was a higher co-contraction index in the sedentary female subjects compared with active female subjects. A preparatory co-contraction period (150 ms before heel strike) was used in this study. The authors suggested that women with lower work-producing capability (as measured on an isokinetic dynamometer at 60°/sec.) have higher preparatory co-contraction. In general, the studies related to walking and running appear to support the hypothesis that during maturation and skill development, inhibition of antagonist muscle groups is thought to be progressively learned until an efficient movement pattern is obtained.[2]

However, multiple discrepancies exist among the studies and make comparisons and conclusions difficult to formulate. Differences that may affect co-contraction include: movement, population, methods and interpretation of findings. In the studies that focused on the continuous, phasic nature of gait (walking and running), similar results were observed. For example, the less experienced individuals seemed to exhibit increased co-contraction of the hamstring and quadriceps. In contrast, the results from various discrete movements (drop jump, vertical jump and side step cut) appear to differ and add complexity to the comparative analyses. Landing and cutting manoeuvres are typically examined in relation to dynamic knee joint stability to protect the joint from excessive load that can cause injury, whereas gait may be more related to questions regarding movement efficiency.

Methodological and technical considerations

Muscular co-contraction results vary among studies based on the population and movement task. However, it is clear that technically, the calculation of a co-contraction index or ratio can be extremely complex and vary markedly among studies. Typically, surface EMG is used to obtain agonist and antagonist muscular activation patterns. The EMG signal is the electrical representation of neuromuscular activation focused at the neuromuscular endplate related to a contracting muscle.[2] Both extrinsic and intrinsic factors may influence the EMG signal that is detected and recorded.[28] Extrinsic factors may include the electrode configuration, electrode location relative to motor points and lateral edge of muscle and electrode orientation with respect to muscle fibres, among other potential factors.[28] Intrinsic factors, such as the number of active motor units, muscle fibre type, blood flow in the muscle, fibre diameter, depth and location of active muscle fibres, and the amount of tissue between surface of muscle and electrode are other important factors that can affect detectable signal intensity.[28]

In addition to the number of anatomical, physiological and technical factors that may affect recorded EMG signals, the specific processing and analysis of the signal are also important to the reported index or ratio.[29,30] Kellis[30] reviewed several factors specifically related to quantification of antagonist activation around the knee. The method of normalising an EMG signal is an important factor that is often performed differently among studies.[29,30] Antagonist EMG is typically normalised to reduce variability and/or to relate the signal contribution to the resultant joint moment.[30] Kellis[30] provided discussion in his review of how the method of normalisation can alter reported results and suggested that standardised methods be considered; a careful interpretation of normalised EMG data was recommended.

Alternative methods

Alternative methods of examining co-contraction have used joint moment analyses, leg and vertical stiffness calculations and model-based estimation of muscle forces. Calculation of joint moments through inverse dynamics incorporates the net forces that act about the joint.[7] One limitation of net joint moment analysis is that it does not indicate which muscles are active or what are the individual muscle forces generated at any specific point in time. Therefore, cautious interpretation of the joint moment to the actual muscle forces is necessary. Joint stiffness calculations involve the resistance of a mechanical stretch by an applied force.[31] Joint stability requires muscle stiffness and may relate to musculoskeletal injury potential.[31] Padua *et al*.[31] found that female subjects had lower leg stiffness values and higher quadriceps to hamstring co-contraction compared with male subjects Although once normalised to mass, the stiffness values were not different, female subjects exhibited greater quadriceps activation than did male subjects.

Other techniques estimate individual muscle forces through computational models. The agonist and antagonist muscle groups can then be further investigated to address co-contraction during different movements. These computer models represent varying degrees of complexity and require detailed information regarding the muscle and skeletal systems.[32] Erdemir *et al* reviewed the various techniques for this type of modelling and provided recommendations for clinical applications[33] These authors suggest that when a clinical problem involves co-contraction and muscle forces cannot be adequately interpreted based on EMG or joint torques, that model-based estimation of individual muscle forces may be necessary.[33] A combination of methods is likely to be necessary to gain a better understanding of how the neuromuscular system uses co-contraction for joint stabilisation and coordinated movements in a timely manner.

Conclusions and further recommendations

Longitudinal study designs should be used to address motor control and learning adaptations that may occur throughout development related to co-contraction of hamstring and quadriceps musculature for both dynamic joint stability and efficient movement patterns. Neuromuscular injury prevention studies may also be beneficial to help address the changes that occur in co-contraction during dynamic activities. The relationship between adequate dynamic joint stability and efficient movement patterns is complex. In high joint force and torque motions, where the hamstring are activated to increase joint stiffness and stabilise the knee, the effectiveness of the quadriceps may be decreased, requiring greater work and reduction of the efficiency of movement. If individual muscle forces can be estimated during these dynamic movements, then the movement control and loading on the ligaments may be better understood.[33]

From the systematic review we conclude the following.

1. Antagonistic co-contraction of hamstring musculature is evident during dynamic closed chained movements.
2. Conflicting relationships of co-contraction to age and skill have been reported.
3. Standardisation of EMG-based methods is an important component for measures of co-contraction based on technical and practical limitations. Alternative methods should be considered and validated.

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What is already known on this topic

- There is a potential complex and conflicting relationship with muscular co-contraction, specifically, between joint stability and movement efficiency.
- Co-contraction levels are high during normal dynamic joint loading movements such as landing.

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What this study adds

- This study systematically reviews and identifies that co-contraction related to age and skill development varies among studies due to technical and practical considerations.
- Adequate antagonistic co-contraction of hamstring musculature appears to be a component of all functional movements to possibly maintain dynamic knee stability and protect against excessive joint loads.

Table 1

Results from database review

Study	Subjects	Tasks	Measures	Findings
Frost *et al*[22]	Grouped by age, years: 7–8 (n = 10); 10–12 (n = 10); 15–16 (n = 10)	Treadmill walk, treadmill jog	EMG, VO_2	Co-contraction index higher at running speeds matched to same relative metabolic intensity in younger age subjects. VO_2 higher for younger age at matched speeds
Croce *et al*[24]	Grouped by age, years: prepubescent girls (n = 15); prepubescent boys (n = 15); postpubescent women (n = 14) ; postpubescent men (n = 14)	Vertical jump landing (50% of maximum)	EMG, kinematics	Co-contraction ratio higher in postpubescent compared with prepubescent before landing. Co-contraction ratio lower in postpubescent compared with prepubescent after initial contact
Hamstra-Wright *et al*[6]	Prepubescent children: boys, high skill (n = 11); boys, low skill (n = 6); girls, high skill (n = 10); girls, low skill (n = 9)	Drop jump	EMG, leg stiffness	Low-skilled prepubescent children had greater preparatory co-contraction than high skilled children. No differences in vertical leg stiffness between gender or skill level
da Fonseca *et al*[21]	Male, athletic (n = 9); male, sedentary (n = 9); female, athletic (n = 9); female, sedentary (n = 9)	Walk, jump landing	EMG	Walking: sedentary females had higher co-contraction levels than athletic females. Landing: no differences between groups
Sigward and Powers[23]	Girls, experienced (n = 15); girls, novice (n = 15)	Side-step cut	EMG, inverse dynamics	Novice athletes had higher co-contraction during early deceleration than experienced athletes. Experience athletes had higher internal knee flexion moments than novice athletes
Russell *et al*[25]	Grouped by age, years. Children: girls (n = 14), boys (n = 14); adults: women (n = 14), men (n = 13)	Vertical jump landing (50% of maximum, normal and perturbed)	EMG, kinematics	Adults had higher co-contraction ratio during preparatory landing phase than did children. No co-contraction ratio differences between groups during reflexive or voluntary phase. No gender difference in co-contraction ratio

EMG, electromyography; VO_2. oxygen uptake.