4-1-2014

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Note. This article will be published in a forthcoming issue of the *Journal of Applied Biomechanics*. The article appears here in its accepted, peer-reviewed form, as it was provided by the submitting author. It has not been copyedited, proofread, or formatted by the publisher.

Section: Original Research

Article Title: Muscle Synergies During a Single-Leg Drop-landing in Boys and Girls

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Journal: *Journal of Applied Biomechanics*

Acceptance Date: October 3, 2013

"Muscle Synergies During a Single-Leg Drop-landing in Boys and Girls" by Kipp K et al.
Journal of Applied Biomechanics

Muscle Synergies during a Single-leg Drop-landing in Boys and Girls

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Funding: The authors would also like to acknowledge assistance from the National Institutes of Health (NIH T-32 HD007422-20).

Conflict of Interest Disclosure: None

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Running Title: Muscle Synergies during Landing

Abstract

The purpose of this study was to investigate muscle activation patterns during a landing task in boys and girls through the use of muscle synergies. Electromyographical (EMG) data from six lower extremity muscles were collected from 11 boys and 16 girls while they performed single-leg drop-landings. EMG data from six leg muscles were rectified, smoothed, and normalized to maximum dynamic muscle activity during landing. Data from 100 ms before to 100 ms after touchdown were submitted to factor analyses to extract muscle synergies along with the associated activation and weighing coefficients. Boys and girls both used three muscle synergies. The activation coefficients of these synergies captured muscle activity during the pre-landing, touchdown, and post-landing phases of the single-leg drop-landing. Analysis of the weighing coefficients indicated that within the extracted muscle synergies the girls emphasized activation of the medial hamstring muscle during the pre-landing and touchdown synergy whereas boys emphasized activation of the vastus medialis during the post-landing synergy. Although boys and girls use similar muscle synergies during single-leg drop-landings, they differed in which muscles were emphasized within these synergies. The observed differences in aspects related to the muscle synergies during landing may have implications with respect to knee injury risk.

Keywords: principal components analysis, factor analysis, biomechanics, anterior cruciate ligament (ACL), injury

Word Count: 3600

Introduction

The incidence rate of non-contact anterior cruciate ligament (ACL) injuries in collegiate athletics is reported to be 2-8 greater in females than in males.[1] Even though epidemiologic data for adolescents and pediatrics are much more limited, Shea et al. [2] reported that ACL injuries in youth soccer players still accounted for 37% of all knee injuries in females and for 24% in males. Despite the apparent presence of sex-specific differences in injury rates, researchers have not conclusively determined why females, or female youths in this case, are more likely to sustain ACL injuries than their male counterparts.[3] Current theories that aim to explain the disparity in ACL injury rates are based on anatomical, hormonal, and neuromechanical differences between sexes.[3]

Although the observed sex bias in ACL injury rates appears to manifest through a combination of factors, neuromechanical factors typically receive the greatest attention because they prospectively predict ACL injury[4] and, more importantly, are amenable to training interventions.[3, 5] Among neuromechanical factors that are thought to contribute to ACL injury, muscle activation patterns have been implicated to play a major role because they are responsible for the dynamic control of joint stability during athletic tasks and thus may influence the joint loading environment. Although a number of studies have focused on the role of muscle activation and co-activation patterns during landing in adults,[6-11] only a handful of studies have examined sex differences among these patterns in adolescents or pre-adolescents.[12-17]

It is of practical importance to study differences in muscle activation patterns between boys and girls before puberty so as to provide clues about the onset of the differences observed in adulthood.[12, 13, 15] To address these important issues, Hamstra-Wright et al.[12] studied the ratio of preparatory hamstring/quadriceps co-activation when performing a landing task in prepubescent subjects, but these authors did not find any sex differences. Similarly, Russell et al.[13] reported no sex differences in co-activation ratios in prepubescent children performing landing tasks. In addition, Medina et al.[14] examined muscle activation patterns in the quadriceps and hamstring muscles during the pre-landing phase of a drop landing in different groups of high school aged subjects, and also did not report any sex differences in the time between onset of muscle activation and initial ground contact for any muscle group. While the aforementioned studies provide some basic information on muscle activation patterns in boys and girls, little is known about the neural control that shapes these patterns in children during dynamic tasks.

Muscle activation profiles are thought to originate from a set of relatively few neural control signals.[18-22] It has been posited that these signals are the output of central pattern generators, which are modulated by integrated cortical and proprioceptive inputs.[19] One approach to study how neural control signals translate into muscle activation patterns is through the use of 'muscle synergies.'[18] A muscle synergy can be defined as the activation pattern of individual or multiple muscles by a single neural control signal from a central pattern generator, and can provide meaningful physiological information about the control of muscle activation at the level of the central nervous system.[19-22] Fundamentally, a muscle synergy consists of a time-invariant weighing coefficient and a time-varying activation coefficient. The weighing coefficients within a synergy determine the number of muscles along with the extent of their activation, while the activation coefficient captures when, during a task, the muscles are active. These variables can also be used to provide information about co-activation patterns. Since an activation coefficient captures a peak of activation that occurs at a distinct point in time, the ratio of the associated weighing coefficients from two antagonistic muscles can capture co-activation patterns at that point in time.[19]

The purpose of this study was to use muscle synergies to investigate differences in muscle activation patterns between boys and girls during a single-leg drop-landing. Specifically, the aim was to compare the weighing and activation coefficients of muscle synergies extracted from EMG data of the lower extremity during a single-leg drop-landing task. It was hypothesized that weighing and activation coefficients would differ between boys and girls, and that these differences would help identify sex differences in muscle activation and co-activation patterns.

Materials and Methods

Subjects

Sixteen girls (mean±SD; age: 11.1±0.5 yrs; height: 1.50±0.10 m; mass: 43.9±14.6 kg) and eleven boys (mean±SD; age: 11.4±0.8 yrs; height: 1.51±0.06 m; mass: 43.2±6.4 kg) were recruited from a local U-11 youth soccer league. Subjects were screened for musculoskeletal conditions that would preclude their safe participation in the study. IRB approval was gained from the human subjects review board at the local academic institution and written informed consent was obtained from the children's guardian before testing began.

Electromyography

Subjects wore short spandex shorts for testing. Their skin was cleaned with an alcohol swab. Self-adhering, pediatric surface electrodes (Ag/AgCl) with inter-electrode distance of 2 cm were placed longitudinally over the belly of six lower extremity muscles (Rectus Femoris, Vastus Medialis, Vastus Lateralis, Medial Hamstring, Lateral Hamstring, and Soleus) according to SENIAM guidelines. Electromyographical (EMG) data were collected with a telemetry system (Noraxon, Scottsdale, AZ, USA). EMG recordings were synched with force plate (Kistler Instrument Corp, Amherst, NY, USA) output through a motion analysis system (Vicon, Lake

Forest, CA, USA) interface. EMG and force plate data were sampled at 1250 Hz. EMG recordings were checked on-line before testing to verify electrode placement and limit cross-talk.

Data Collection

Data were collected during the execution of a single-leg landing task. The starting position for this task involved subjects hanging from a horizontal bar with arms straight overhead and their feet 30 cm off the ground. The execution of the maneuver then required subjects to self-initiate the release from the bar, land on a force plate with their dominant limb, and upon landing stabilize their body over the landing leg. Five successful trials were collected for each subject. All EMG data were collected from approximately a second before subjects let go of the bar to several seconds after landing. The EMG data were then trimmed to 100 ms before to 100 ms after touchdown, which was defined as the instant when the vertical component of the ground reaction force exceeded 10 Newtons.

Data Processing

All EMG data were full-wave rectified, smoothed with a zero-lag 4th order, low-pass Butterworth filter at 6 Hz,[16] and amplitude-normalized to peak activity during the single-leg landing.[23] The processed EMG data were then linearly interpolated to 101 data points with touchdown occurring in the middle of the 200 ms time period for which data was collected (Figure 1). Ensemble averages were then calculated from the processed EMG recordings of all six muscles from each subject’s successful trials. The six ensemble averages from all subjects were then pooled and combined into two data matrices (i.e., one for the boys and one for the girls). The data matrix for the boys thus consisted of 66 rows (Six muscles x 11 boys) by 101 columns (interpolated processed EMG envelope), whereas the data matrix for the girls consisted of 96 rows (Six muscles x 16 girls) by 101 columns (interpolated processed EMG envelope).

These two data matrices were then used as inputs to a factor analysis.[18, 24, 25] The steps for this analysis involve calculating the correlation matrix of each input matrix, extracting the initial principal components (PCs), and applying a varimax rotation to the extracted PC's.[23] Next, factors scores (activation coefficients), factor loadings (weighing coefficients), and percent of variance accounted for (VAF) for each PC were calculated.[18] These operations effectively reduce the dimensionality of the EMG waveforms similar to a traditional factor analysis, but in the case of using continuous time-series data as opposed to discrete data points, the resultant PC's represent a set of functions, or in the case of pooled EMG signals, describe muscle synergies.[21, 22, 26] The activation coefficients capture time-dependent activation of a muscle, whereas the weighing coefficients capture the amplitude of a muscles' activation for a given synergy (Figure 2).[21] Between-subject comparisons of a muscles' weighing coefficient can thus provide information about how "much" each subject activates that muscle within the muscle synergy. Further, since each activation coefficient captures activation of a muscle that occurs at a distinct point in time, the ratio between the associated weighing coefficients from two opposing muscles can be used to assess the ratio of co-activation between antagonistic muscles.[20] Medial/lateral co-contraction ratios were calculated between the medial-lateral hamstring muscles (MH/LH) and the medial-lateral quadriceps muscles (MQ/LQ). Anterior/posterior co-contraction ratios were calculated between the medial quadriceps and hamstring muscles (MQ/MH) and the lateral quadriceps and hamstring muscles (LQ/LH). It should be noted that co-activation ratios were only calculated from weighing coefficients for the same activation coefficient (e.g., MH and LH weighing coefficient from the first activation coefficient or synergy). Weighing coefficients and co-activation ratios were used for statistical analysis.

Statistics

Separate general linear models were used to compare weighing coefficients and co-activation ratios between boys and girls. The standard of proof for statistical significance was set at an alpha-level of 0.05. Statistical trends were investigated at a p-value below 0.10. All statistical analyses were performed with SPSS 17.0. All data are presented as mean±SD.

Results

The factor analysis extracted three principal components (i.e., muscle synergies) from the EMG data of both boys and girls during the single-leg drop-landing task. In order of extraction, the variance accounted for by each of the three principal components was 33.5, 32.6, and 31.7% for the boys and 37.1, 31.2, 27.6% for the girls. Inspection of the activation coefficients associated with each muscle synergy indicated that for both groups the first activation coefficient captured muscle activation at touchdown (Muscle Synergy 1), the second activation coefficient captured muscle activation during the pre-landing phase (Muscle Synergy 2), and the third activation coefficient captured muscle activation during the post-landing phase (Muscle Synergy 3) (Figure 3).

The statistical comparisons between weighing coefficients indicated that boys and girls differed in three instances (Figure 4). Specifically, girls displayed greater weighing coefficients for the medial hamstring at touchdown than boys (Muscle Synergy 1 – Medial Hamstring; girls: 3.36±1.73; boys: 1.76±1.69; $p = 0.025$). Conversely, boys displayed greater weighing coefficients for the vastus medialis during the post-landing phase than girls (Muscle Synergy 3 – Vastus Medialis; boys: 3.34±0.38; girls: 2.64±0.89; $p = 0.011$). In addition, there was a trend towards statistical significance that indicated girls may display greater weighing coefficients for the medial hamstring during the pre-landing phase than boys (Muscle Synergy 2 – Medial

Hamstring; girls: 1.92±1.28; boys: 0.99±1.49; $p = 0.093$). The statistical analysis did not identify any significant differences between the co-activation ratios of any weighing coefficients for boys and girls.

Discussion

The purpose of this study was to investigate lower extremity muscle activation patterns in boys and girls during a single-leg drop-landing task through the use of muscle synergies. Although, boys and girls used the same number of muscle synergies and similar activation coefficients during landing, the groups used different weighing coefficients. Specifically, these differences were characterized by greater medial hamstring weighing coefficients at touchdown and during the pre-landing phase in girls, but greater vastus medialis weighing coefficients during the post-landing phase in boys within the respective muscle synergies. Therefore, it appears that within the extracted muscle synergies, girls emphasized activation of the medial hamstring muscle during the pre-landing and touchdown synergy whereas boys emphasized activation of the vastus medialis during the post-landing synergy.

The overall muscle activation patterns during the single-leg drop-landing for both boys and girls could be represented by three muscle synergies. For each muscle synergy, activation coefficients captured time-varying peaks in muscle activation, which occurred during one of three phases: 1) at touchdown, 2) pre-landing, and 3) post-landing. It has been suggested that muscle activity during locomotion is driven by relatively few muscle synergies and that a larger number of synergies indicates a more complex control strategy.[21, 25] Hence, the similar number of muscle synergies as displayed by boys and girls would indicate a comparable neural control strategy during the single-leg landing task. It may be of interest to briefly consider another implication of a three-peak muscle activation profile during a drop-landing task, because most studies dichotomize muscle activity during landing into pre- and post-landing muscle activation. While the present results partially support this convention, they also reveal that a peak of muscle activation occurred around the point of foot touchdown. Since the analyses revealed a sex difference for variables related to the muscle synergy at touchdown, it may be prudent to consider similar analyses in future studies so as to not overlook these differences, which may otherwise be inadvertently washed out with conventional analyses.

The variance proportion associated with each of the three muscle synergies differed slightly between boys and girls. The distribution of variance proportions explained by each muscle synergy may reflect how dominant each synergy was with respect to the overall muscle activation profile during the single-leg drop-landing task. Based on the distribution, it appeared that boys used all three muscle synergies to roughly the same extent during landing, whereas girls seemed to emphasize the synergy related to muscle activation at touchdown and deemphasized the synergy related muscle activation after landing. Croce et al.[15] hypothesized that among pre-pubescent subjects, the emphasis on muscle activation prior to landing reflects a muscle activation strategy that is pre-programmed, whereas muscle activation after ground contact reflects a more reactive strategy. Based on this hypothesis it appears that girls in the current study may have emphasized more pre-programmed and less reflexive muscle activation strategy. Since proper activation of muscles via pre-programmed strategies has been suggested to be crucial to control ground reaction forces and anterior tibial displacement during landing tasks,[10, 15] the muscle activation strategy used by the girls in the current study may represent a better method to deal with the vigorous requirements imposed by the dynamic landing task.

While the number of muscle synergies and activation coefficients did not differ between boys and girls, several between-group differences in the weighing coefficients within each muscle synergy were found. Given that weighing coefficients determine which muscles are activated within a particular muscle synergy, a difference between weighing coefficients translates into muscle-specific differences in activation at discrete time points during landing (i.e., during the time interval specified by the activation coefficient). In the current study, weighing coefficients for the medial hamstring muscle were greater for girls than boys during the pre-landing phase and at touchdown. This difference would indicate that the respective pre-landing phase and touchdown muscle synergies for girls were characterized by more dominant activation of the medial hamstring muscles. In addition, girls displayed smaller weighing coefficients for the vastus medialis during the post-landing phase than compared to boys. Collectively, it therefore appears that girls used muscle synergies that encompassed a more hamstring-dominant activation pattern in preparation for landing, but a less quadriceps-dominant activation pattern after landing. These findings are in contrast with the theory that adult females tend to use a quadriceps-dominant landing strategy.[4, 5] A quadriceps-dominant strategy is characterized by unbalanced activation of the quadriceps over the hamstring muscles, which is thought to increase anterior tibial shear forces and promote excessive ACL strain during the landing.[4, 5] Moreover, activation of the medial hamstring and quadriceps muscles over their lateral counterparts is linked to less deleterious landing mechanics, in that greater medial activation of these muscles is associated with smaller frontal plane knee joint angles and torques,[27, 28] both of which have been posited as risk factors for ACL injury.[4] Therefore, considering the functional roles of the hamstring and quadriceps muscles with respect to ACL loading and injury,[29, 30] these results would imply that boys displayed a more injurious muscle activation pattern as implicated within the ACL injury mechanism.

Despite the presence of sex differences in weighing coefficients between boys and girls, these differences did not affect any of the co-activation ratios. Several authors have similarly reported that co-activation ratios were not affected by the sex of prepubescent subjects.[12, 15] The lack of differences in co-activation ratios between weighing coefficients was somewhat surprising, especially given the aforementioned differences for some of the muscles. It is difficult to explain this result, but since the co-activation ratio is calculated from two values it may be that a significant finding in one of these values is negated by a non-significant trend in the opposite direction of the other value. Another conceivable explanation lies in the normalization method of the EMG data. More specifically, the normalization of EMG to a dynamic task maximum may have masked differences in co-activation ratios. Nevertheless, given that the majority of studies on muscle activation patterns during landing tasks in pre-adolescent or adolescent subjects have found no differences in either muscle activation or co-activation patterns,[12, 13, 15] the disparity between a portion of the results from the current study and those previously reported may indicate that the use of muscle synergies provides a sensitive approach to examine sex-specific differences in the control of muscle activations during landing tasks. It may be particularly beneficial to examine muscle synergies after training interventions to help identify if and/or how the central nervous system reorganizes its control strategy in response to targeted training efforts. In addition, use of other normalization methods, which account for the overall global magnitude of muscle activation, may help further elucidate sex-specific differences in muscle synergies and their influence on neuromechanical risk factors of ACL injury.

Although the results from this study provide novel insight into muscle activation patterns for boys and girls, the findings should be interpreted carefully in light of several limitations. Subjects were comparable in age because they were recruited from a U-11 soccer league. Boys and girls, however, mature at different rates, which may imply that not all subjects were at the same stage of maturation. Since neuromechanical performance changes with maturation,[31-33] future studies may be needed to more clearly elucidate the sex differences in muscle synergies across a wider range of subjects to more clearly identify the effects of maturation. While the recruitment of similarly aged subjects from the same league may be serve as a potential confounder to the results of the current study, it also helped ensure comparable practice/competition exposures and skill/experience levels between groups, factors all of which affect the control of muscle activations and may ultimately influence injury risk.[3, 12] So despite the fact that recruiting subjects of similar age may serve as a limitation, it also served to control for other confounders. It may also be prudent to briefly consider the normalization procedure used in this study. All EMG data were normalized to the maximum amplitude observed during the landing task. While this normalization procedure is used within parts of factor analyses,[23] amplitude-based comparisons may be limited to within or between the respective synergies that are extracted from such analyses. This method, therefore limits the interpretation of magnitude-based, between-groups differences of muscle activation magnitude.

The boys and girls in this study used similar muscle synergies to control muscle activation patterns before and after landing as well as at foot touchdown during a single-leg drop-landing. Despite these similarities, however, a portion of the results point to differences in the emphases of muscle synergies, which translated into greater medial hamstring muscle activity at touchdown and during the pre-landing phase in girls, but greater vastus medialis activation during the post-landing phase in boys. From these findings it may be suggested that the muscle synergies associated with muscle activation patterns used by the girls were more consistent with an ACL protective strategy, whereas in boys these patterns were more consistent with those implicated within the ACL injury mechanism. Further investigations that examine muscle synergies after training or over the course of maturation may help elucidate differences in muscle activations between boys and girls and how they manifest within the proposed ACL injury mechanism.

Acknowledgements

The authors would also like to acknowledge assistance from the National Institutes of Health (NIH T-32 HD007422-20).

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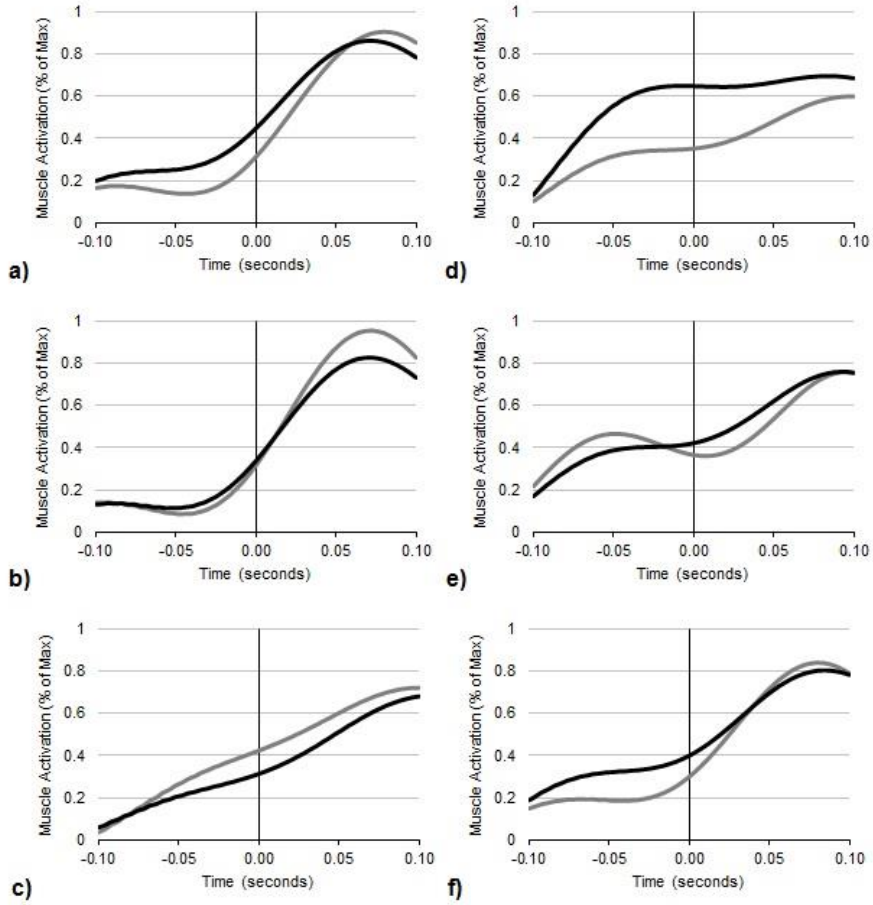

Figure 1 – Normalized ensemble-average muscle activation profiles of the **a)** rectus femoris, **b)** vastus medialis, **c)** vastus lateralis, **d)** medial hamstring, **e)** lateral hamstring, **f)** soleus for boys (grey lines) and girls (back lines) during the single-leg landing task.

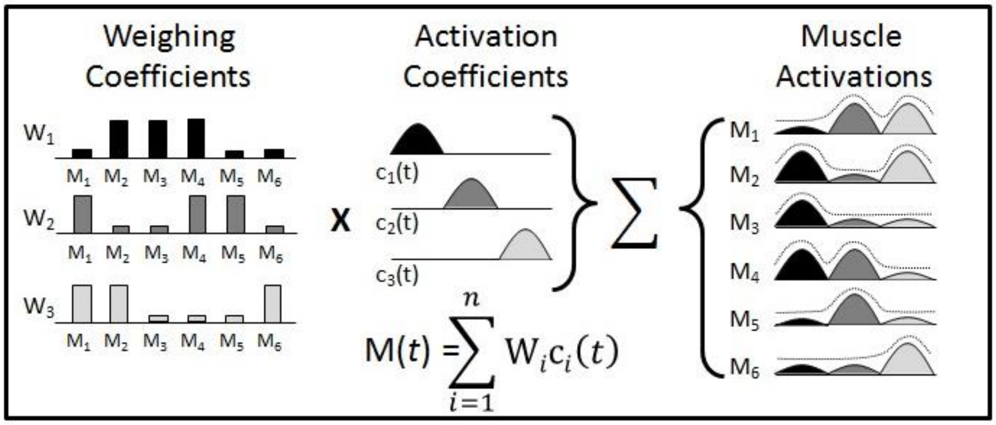

Figure 2 – Analysis of Muscle Synergies. The activation of each individual muscle (M_1-M_6) is determined by a weighing coefficient (W) and activation coefficient (c) of each muscle synergy. Note that the weighing coefficients determine how many muscles are recruited within a synergy along with how much the muscles are activated, while the activation coefficient captures when the muscles are active. The figure shows three muscle synergies (black, dark grey, and light grey shading) that contribute to the overall EMG profiles.

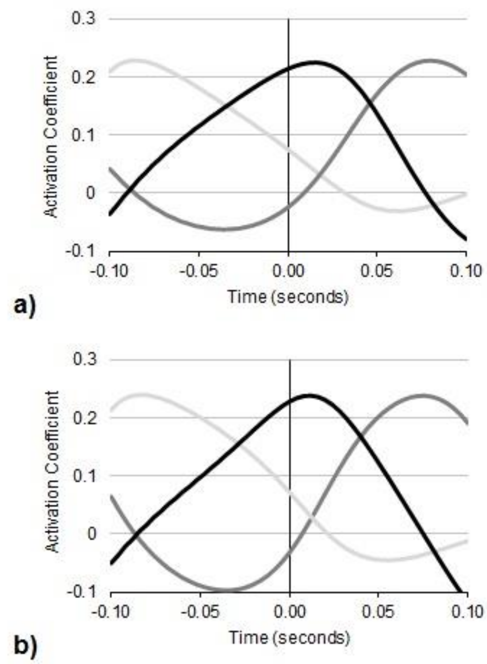

Figure 3 – Activation coefficients (in arbitrary units) for **a)** boys and **b)** girls during the single-leg landing task (Black line = Muscle Synergy 1, light grey line = Muscle Synergy 2, dark grey = Muscle Synergy 3).

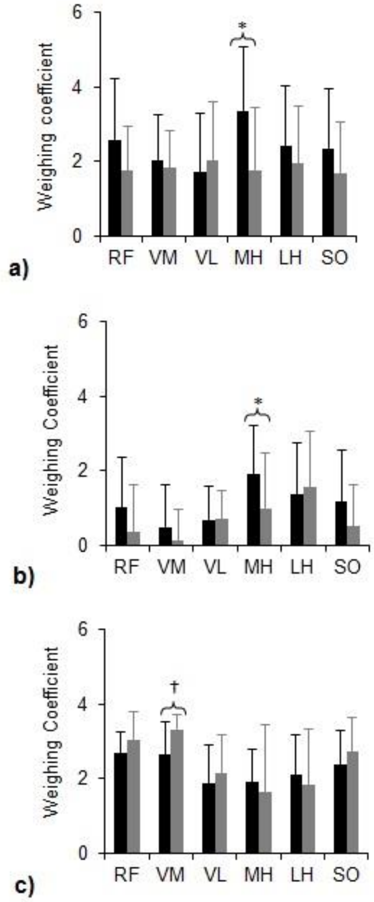

Figure 4 – Weighing coefficients (in arbitrary units) for **a)** muscle activation coefficient at touchdown (Muscle Synergy 1), **b)** muscle activation coefficient before landing (Muscle Synergy 2), and **c)** muscle activation coefficient after landing (Muscle Synergy 3). Rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), medial hamstring (MH), lateral hamstring (LH), and soleus (SO). (Black bars = Girls, Grey bars = Boys). $^{*}p < 0.10$ for boys vs. girls, $^{\dagger}p < 0.10$ for boys vs. girls