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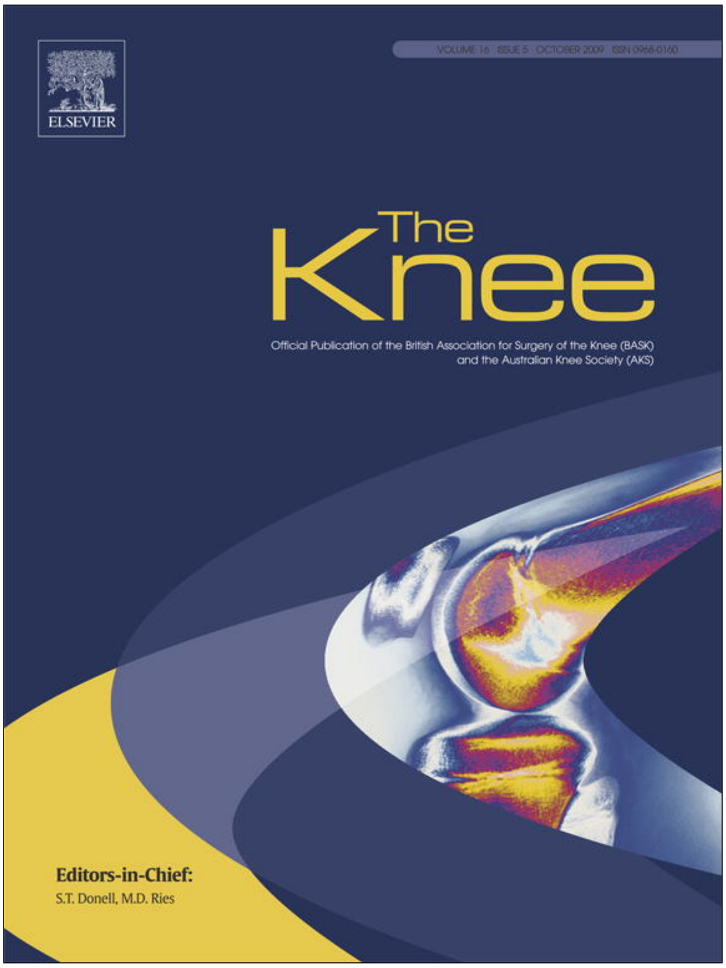


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The Knee 16 (2009) 375–380

Contents lists available at ScienceDirect

The Knee

# Gender differences in onset timing and activation of the muscles of the dominant knee during stair climbing

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ARTICLE INFO

*Article history:*
Received 28 June 2008
Received in revised form 5 February 2009
Accepted 7 February 2009

*Keywords:*
Gender
Knee stabilization
Muscle activation time delay
Electromyography
Vastus medialis muscle
Stair climbing

ABSTRACT

An electromyographical analysis (EMG) of knee muscle activation patterns and time delays has rarely been discussed in the literature. The purpose of this study was to compare the activation time and EMG amplitude of the dominant vastus medialis and medial hamstring muscles during stair climbing. Fifteen male and 18 female subjects participated in this study. The subjects were asked to ascend and descend 14 steps, five times. There was a significant time delay difference between genders during stair climbing ($F=8.37$, $p=0.008$). The female subjects demonstrated longer time delays while descending the steps. In addition, the female subjects demonstrated significantly lower normalized EMG amplitude during down stair climbing ($F=5.77$, $p=0.025$) while the male subjects demonstrated higher normalized EMG amplitude for the vastus medialis muscle while descending the steps. These results suggest that female subjects possess an increased risk factor for knee injuries during down stair climbing due to muscle activation delays with decreased vastus medialis muscle activity.

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## 1. Introduction

Stair climbing can be a challenging task for some individuals, especially since it is a frequently performed daily activity. Ascending and descending steps are stressful functional activities due to continuous lower extremity weight bearing as well as acceleration and deceleration during each step. An understanding of the mechanisms of the lower extremities during stair climbing is an important step toward greater knowledge of the functioning of the knee joint.

Most subjects with knee pain complain of difficulty with stair climbing. However, there is a lack of investigation regarding electromyography (EMG) analysis during stair climbing, especially lower extremity dysfunction, between genders. Although several studies were conducted to analyze biomechanical performance differences [1–4], these studies were performed during weight bearing activities in a controlled laboratory environment. Based on their results, biomechanical measures of neuromuscular control indicated that strength imbalances exist with increased injury rates among females [5,6]. As a result, there has been an emphasis on monitoring phasic muscle activities around the knee joint based on EMG amplitude and delay time in female subjects during repeated activities, such as stair climbing.

It has been reported that individuals should perform competitive activities requiring effective control with lower extremity stability in order to prevent knee injuries [3,7,8]. These injuries are linked with sudden deceleration and decreased neuromuscular control about the knee in female athletes [4,7,8]. As a result, one of the primary goals of rehabilitation following a knee injury is neuromuscular control of the knee joint based on the amplitude and delay time of EMG activities. A major rehabilitation challenge, however, is weakness of the vastus medialis muscle, which needs to be further investigated [9,10]. In addition, the importance of the initiation and progression of knee problems is still poorly understood [11]. Previous analyses measuring the kinetics of the lower limbs have shown that greater knee moments were required during stair climbing tasks than in level walking [12,13]. Comparison of the activation level of lower limb muscles also reveals higher activation of the knee extensor muscles (vastus lateralis and medialis) and medial hamstring muscles during up stair climbing than level walking [14]. Therefore, it is important to investigate kinematic and EMG analyses of knee muscle groups recruited during up–down stair climbing.

In our previous study, the characteristics of muscle performance were reported based on the dominant and non-dominant sides of the trunk area [15]. The results indicated that the characteristics of the trunk muscles on each side need to be considered in order to understand neuromuscular control during activities. Likewise, as one limb demonstrated increased dynamic control as a result of an imbalance in muscular strength and recruitment patterns, it is evident that dependence on the dominant limb can increase stress on the joints of that extremity [3,16]. In addition, male and female subjects often adopt different body alignments during competitive activities. However, the underlying mechanism of dominance related to knee injuries that occur in females has yet to be delineated.

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doi:10.1016/j.knee.2009.02.003

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**Fig. 1.** The EMG sensing unit consists of the motion sensor and command module components. KinetiSense Biokinetic Analysis System (Cleveland, OH).

Therefore, the purpose of this study was to compare both the amplitude and delay time of EMG activation of the dominant vastus medialis and medial hamstring muscles, as well as any gender differences that may exist, during stair climbing. It was hypothesized that female subjects would demonstrate delayed activation of the dominant vastus medialis muscle in order to prepare for stabilization during repeated stair climbing, especially when descending steps.

## 2. Materials and methods

### *2.1. Participants*

Thirty-three volunteers with various backgrounds were recruited from represented populations in the Cleveland, Ohio area. Subjects were eligible to participate if they: 1) were 21–65 years of age and 2) had reported symptoms of dominant knee pain without pain referral into the lower extremities. Subjects were excluded from participation if they: 1) had additional injuries or had undergone surgery to the lower extremities, with the exception of a partial meniscal injury or minor collateral ligament injury in the knee joint or a partial meniscectomy in the injured or contralateral knee, 2) had a diagnosed psychological illness that might interfere with the study protocol, 3) had overt neurological signs (sensory deficits or motor paralysis), 4) had diagnosed spinal deformities or previous spine surgery, or 5) were pregnant. Those subjects who met the inclusionary criteria received information regarding the purpose and methods of the study and signed a copy of the Institutional Review Board approved consent form.

Subject preference (or limb dominance) was evaluated using a modified Edinburgh inventory [17] based on the performance of ten everyday tasks. The Edinburgh inventory measure ranges from −100 for strong left dominance to +100 for strong right dominance. In our study, the dominant side of the lower extremities followed the same side as the dominant upper extremity.

Each subject's level of pain was inferred from self-reported scores on the Million Pain Interference Visual Analogue Scale (MVAS). An MVAS score for pain intensity provides a way to quantify a "measure" of a patient's knee pain [18]. The MVAS includes 15 questions; each is answered by marking a point on a 10-cm horizontal line with descriptors at each end ("No Pain" on the left and "Worst Possible Pain" on the right). Responses range from 0–100 mm, where 100 represents maximum disability. The subject was asked to mark the line at a point corresponding to the greatest severity of his/her pain at the time the survey was completed. This recorded average distance was interpreted as a percentage of the subject's knee pain intensity.

### *2.2. Procedures*

The staircase used in the study consisted of 14 steps extended at the top by a 2 m walkway to prevent deceleration during stair climbing. The task was to climb the stairs with the greatest riser height that subjects thought they could climb without outside support or use of their hands. Each subject performed the up–down stair climbing task for five repetitions (Fig. 1). The slope of the stairs was 33° with risers of 17 cm, tread depths of 26.0 cm, and a width of 107 cm.

The amplitude of the muscular response was measured by EMG using a pair of bipolar, Ag–AgCl surface recording electrodes with snap connectors (MVAP Electrode, Newbury Park, California) placed on the vastus medialis and medial hamstring muscles. The electrodes were placed on the muscle belly about one third of the distance from the insertion of each muscle and then oriented parallel to the direction of the tested muscle fibers according to Zipp [19]. The data was synchronized with that given by the acceleration channel, and all EMG signals were visually checked for possible interference before processing. The reference electrode was placed on the left lateral malleolus.

The amplitude and delay time were defined and measured from the EMG sensing unit (KinetiSense, CleveMed, Cleveland, Ohio). Each unit consisted of two parts including a sensor unit and a command module that sampled at 75 Hz. The sensor unit consisted of a small, lightweight plastic enclosure that housed a flex circuit with three orthogonal micro-electrical–mechanical (MEMS) piezoelectric acceleration sensors and three orthogonal MEMS gyroscopes. The sensor module was connected to a command module with a thin cable. The command module supplied power, transmitted data via a wireless link, and amplified and acquired two EMG channels. An embedded Bluetooth radio wirelessly transmitted data to a base station computer approximately 20 ft away. Each subject had two sensor units adhered to his/her skin using double-sided tape. The command module was clipped onto an elastic belt worn below the subject's dominant knee.

The EMG signals were pre-amplified at the electrode site (gain 35×) and further amplified downstream in the primary amplifier/processor unit. Full bandwidth EMG data was reduced (20 Hz–500 Hz) using a root mean square (RMS) algorithm to produce EMG envelopes and was high-pass filtered with a cut-off frequency of 10 Hz. These envelope data were the basis for subsequent processing.

All subjects received the same instruction to maintain their standing stability during stair climbing in response to each repetition. During the stair climbing task, subjects stood on ground level in front of the staircase before ascending the first step. All subjects were instructed to place only one foot on each step and to perform at the speed they felt most comfortable (natural speed), as if they were out taking a stroll. The subjects practiced before collecting data until they felt that they performed each task naturally. The amplitude of EMG and delay time were measured by recording the angular rate through a data acquisition system and analyzed by the BioCAT software (Valencia, CA). The delay time was defined as the difference between the time at foot step according to the peak point of acceleration

**Table 1**
Summary of subject demographics.

| Variable | Total | Males | Females | Statistic | $p$ |
|---|---|---|---|---|---|
| $N$ | 33 | 15 | 18 | | |
| Age (years) | | | | | |
| Range | 21–61 | 21–61 | 22–56 | $t=-0.03$ | 0.97 |
| Mean ± SD | 32.00 ± 11.67 | 49.89 ± 7.99 | 32.07 ± 13.24 | | |
| Body weight (kg) | | | | | |
| Range | 48.99–105.23 | 56.70–102.06 | 48.99–105.23 | $t=2.56$ | 0.01* |
| Mean ± SD | 69.39 ± 14.60 | 75.65 ± 11.44 | 63.12 ± 15.04 | | |
| Height (cm) | | | | | |
| Range | 154.94–187.96 | 167.64–187.96 | 154.94–180.34 | $t=5.49$ | 0.001** |
| Mean ± SD | 171.37 ± 9.47 | 178.37 ± 5.74 | 164.83 ± 7.35 | | |

*$p<0.05$. **$p<0.01$.

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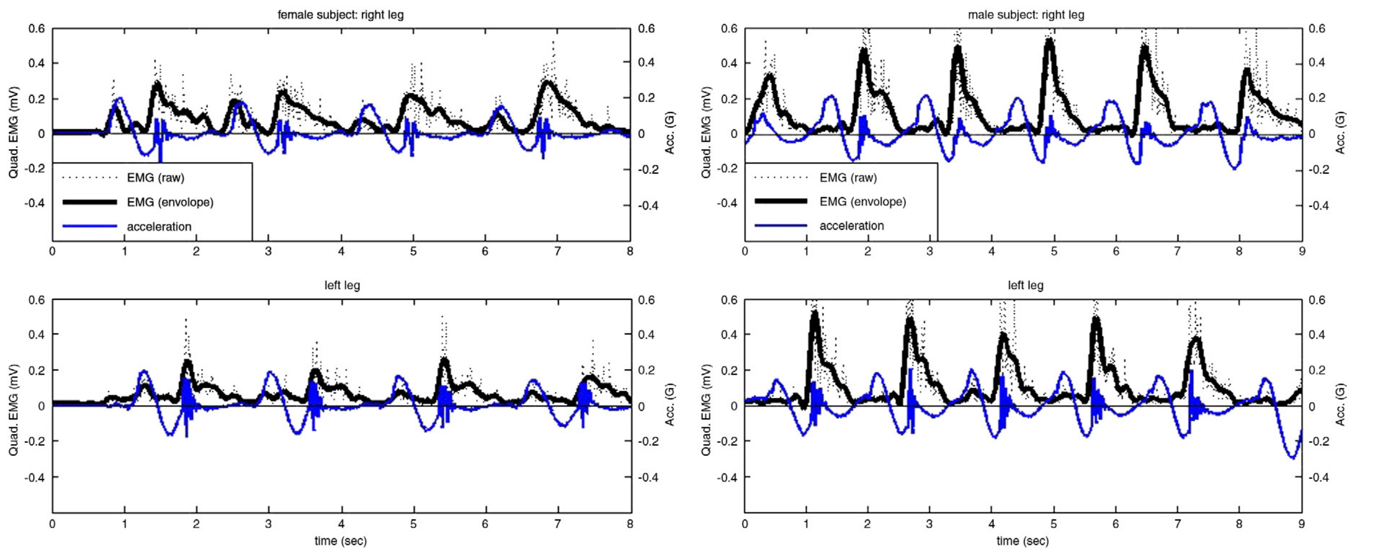


**Fig. 2.** An example of a comparison between the right and left vastus medialis muscle activation patterns for each gender during acceleration. The male subjects demonstrated higher EMG values for both the right and left vastus medialis muscles; however, the female subjects demonstrated double/triple EMG peaks during stair climbing.

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perpendicular to the ground and the first vertical peak of the EMG amplitude. The peak was determined based on the third standard deviation from the average amplitude. The EMG amplitude during each step was the height of the peak during heel-strike, which was normalized based on the individual maximum amplitude.

### 2.3. Data analysis

Statistical analyses were completed using SPSS™ 15.0 (SPSS, Inc. Chicago, IL). Normality was assessed for each of the dependent variables (EMG amplitude and delay time) by the Kolmogorov–Smirnov test. A mixed repeated measure analysis of variance (ANOVA) was used for each dependent variable to determine the main effects of group (gender), stair climbing type (up and down stair climbing), and number of steps (14 steps). The group factor was a between-subjects comparison, and the stair climbing and steps variables were within-subjects comparisons. Possible confounding effects were assessed by completing independent group *t*-tests with anthropometric variables, such as age, body weight, and height variables. Covariates included variables for body weight (kilogram, kg) and height (centimeter, cm) since there were significant differences between genders. For all statistical tests, type I error rate was set at 0.05.

## 3. Results

### 3.1. Subjects

All subjects were right side dominant, and other anthropometric information was obtained from health screening forms and confirmed with each subject's body weight, height, and age. Fifteen male and 18 female subjects participated in this study (Table 1). Based on gender, age (mean ± SD: 49.9 ± 7.9 years for males and 32.1 ± 13.2 years for females) was not significantly different ($t = -0.03$, $p = 0.97$). However, the male subjects had higher body weight (mean ± SD: 75.6 ± 11.4 kg for males and 63.1 ± 15.0 kg for females) ($t = 2.56$, $p = 0.01$) and height measurements (mean ± SD: 178.3 ± 5.7 cm for males and 164.8 ± 7.3 cm for females) ($t = 5.49$, $p = 0.001$) compared to the females.

Pain scores obtained from the MVAS were 18.27% ± 2.02% for the female group vs. 19.53% ± 5.82% for the male group. As a result, there was no significant difference between genders ($t = 0.24$, $p < 0.807$).

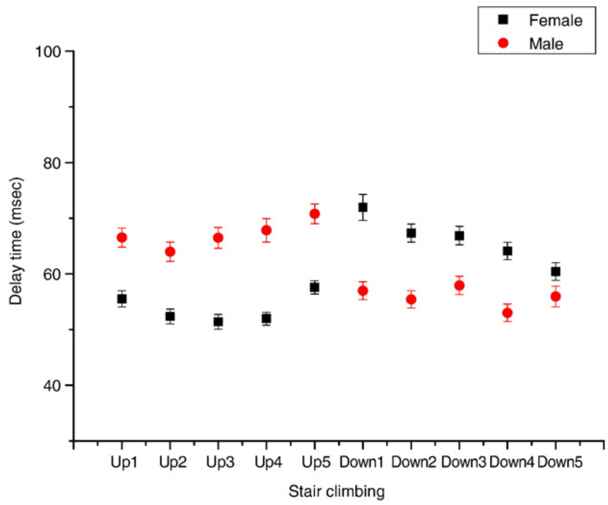


**Fig. 4.** The delay times for the dominant vastus medialis muscle for each gender during repeated up–down stair climbing. The male subjects demonstrated longer time delays while ascending the steps. The female subjects, however, demonstrated longer time delays while descending stairs. As a result, there was a significant gender difference in delay times during stair climbing ($F = 8.37$, $p = 0.008$). The bar indicates standard error values.

### 3.2. The normalized amplitude of EMG

As Fig. 2 indicates, the male and female subjects demonstrated higher EMG values for both the right and left vastus medialis muscles. In addition, the right leg of all subjects had a maximum acceleration at approximately 90 ms while the left leg demonstrated a maximum acceleration at 130 ms. The subsequent maximum acceleration values were about 250 ms for the right leg and 300 ms for the left leg. Therefore, the subjects' gait patterns during stair climbing were consistent.

The EMG amplitude during stair climbing was measured and analyzed. As Fig. 3 indicates, the main effect of stair climbing was analyzed during up and down stair climbing. Overall, there was a significant interaction between genders ($F = 5.77$, $p = 0.02$). During down stair climbing, or eccentric contraction of the vastus medialis muscle, the female subjects demonstrated significantly lower

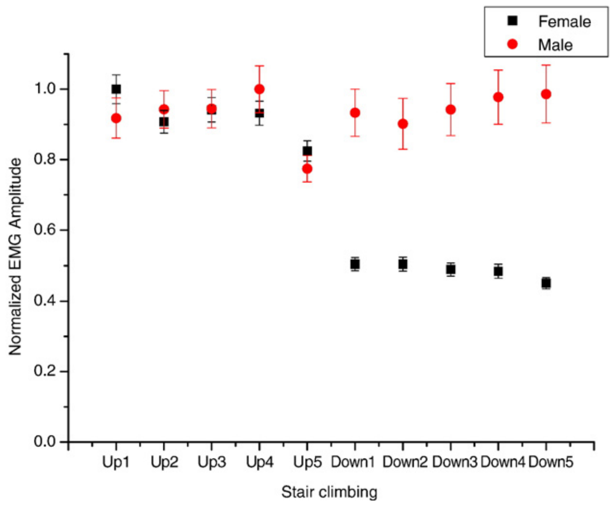


**Fig. 3.** The normalized EMG amplitude of the dominant vastus medialis muscle for each gender during stair climbing. The male subjects demonstrated higher EMG amplitude while descending the steps (eccentric contraction). However, the female subjects demonstrated significantly lower EMG values during down stair climbing. There was also a significant interaction between up–down stair climbing and gender ($F = 5.77$, $p = 0.025$). The bar indicates standard error values.

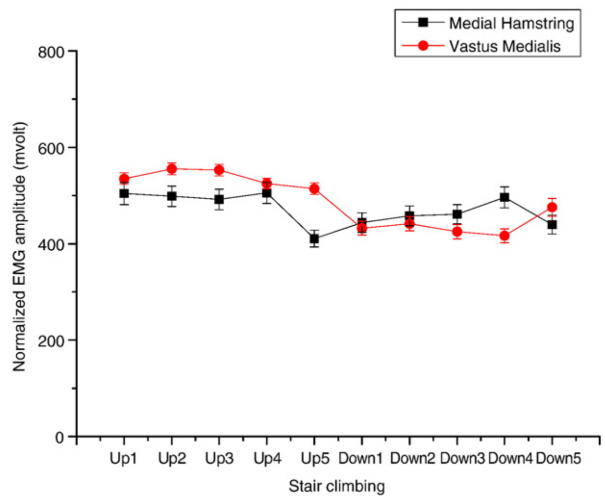


**Fig. 5.** The normalized EMG amplitude of the dominant knee muscles during stair climbing. The vastus medialis muscle demonstrated higher EMG amplitude while subjects ascended the steps (concentric contraction). However, the medial hamstring muscle demonstrated higher EMG amplitude while subjects performed down stair climbing. The bar indicates standard error values.

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normalized EMG amplitude values compared with the male subjects. In order to clarify any effects of confounding factors for this difference, the covariates were analyzed. However, there were no interactions with weight ($F = 2.37$, $p = 0.13$), height ($F = 1.14$, $p = 0.29$), or age ($F = 0.88$, $p = 0.36$) for each gender. Therefore, the results of the normalized EMG amplitude indicated that there was a significant difference between genders, especially during down stair climbing.

The EMG amplitude was compared with the effect of side dominance as well, and there was a significant interaction with gender ($F = 6.07$, $p = 0.02$). As a result, the dominant vastus medialis muscle demonstrated significantly higher EMG amplitude values compared with the non-dominant side during stair climbing.

Fig. 4 indicates the normalized EMG amplitude values of the dominant knee muscles during stair climbing. The vastus medialis muscle demonstrated higher EMG amplitude while subjects ascended the steps (concentric contraction). However, the medial hamstring muscle demonstrated higher EMG amplitude during down stair climbing (eccentric contraction).

### 3.3. Delay time

The delay time (ms) of the vastus medialis muscle was analyzed based on EMG response during stair climbing. There was a significant gender difference in delay times during stair climbing ($F = 8.37$, $p = 0.008$). As shown in Fig. 5, the male subjects revealed a longer delay time (up: $67.13 \pm 18.33$, down: $55.86 \pm 16.46$) than the female subjects (up: $53.77 \pm 12.96$, down: $66.14 \pm 17.59$) during concentric contraction of the vastus medialis muscle while ascending the stairs. However, the female subjects demonstrated a longer delay time during eccentric contraction of the vastus medialis muscle while descending the stairs ($F = 6.14$, $p = 0.02$). Therefore, there was a significant difference in delay time between genders.

The effects of confounding factors were analyzed based on the covariates. There were no interactions with body weight ($F = 1.55$, $p = 0.19$), height ($F = 1.76$, $p = 0.14$), or age ($F = 1.05$, $p = 0.38$) for each gender. Delay time was compared with the effect of side dominance, and there was a significant interaction with gender ($F = 4.64$, $p = 0.04$). Therefore, the dominant vastus medialis muscle was significantly faster compared with the non=dominant side during stair climbing, especially among male subjects.

## 4. Discussion

The results of this study indicated that there was a significant gender difference in the normalized amplitude of EMG as well as in the time delay of the dominant vastus medialis muscle during stair climbing. The EMG amplitude was significantly higher on the dominant side for the male subjects during down stair climbing. In addition, the male subjects revealed a significant time delay during concentric contraction of the vastus medialis muscle while ascending the steps.

The results of the current investigation support previous studies for both male and female subjects. However, a study by Zeller et al. reported that females display greater total muscle activation of the vastus medialis muscle than males [20]. While this study, along with others, may suggest that females tend to exhibit a vastus medialis dominant means of producing dynamic knee stability, further research is needed to elucidate this possible gender difference as there is little empirical information [21–24]. The results of our study indicated that there were differences based on gender and muscle activation patterns of the dominant side of the vastus medialis during stair climbing. The overall EMG activation of the vastus medialis muscle was similar in both genders while subjects ascended the stairs. However, the female subjects revealed significantly lower amplitude of EMG values while descending the steps compared with the male subjects. It is important to maintain vastus medialis strength and dynamic stability during stair climbing since muscle strength and motor control are needed to dampen the effects of the additionally generated momentum of the knee [25].

The differences in amplitude and proprioceptive acuity of knee movements could be determined an asymmetrical process in knee patients [26–29]. However, regardless of leg dominance, the average side-to-side strength differential was approximately 11% [30]. Knapik et al. reported increased lower extremity injury rates in female athletes demonstrating 15% strength deficits of either the left vastus medialis or hamstring muscles [5]. Therefore, the dominant vastus medialis muscle is important although our study did not emphasize other muscle groups, such as the tibialis anterior or back muscles.

The delay time was longer while the male subjects ascended the stairs and shorter while they descended the stairs. The data obtained from the female subjects were opposite those of the male subjects. Therefore, there were significant differences in delay times of the vastus medialis muscle during stair climbing, which might demonstrate a preferential inhibitory effect on the hamstrings. During up stair climbing, the knee extensor muscles have a dominant role in the progression from one step to the next and are assisted by the ankle plantar flexors and the hip extensors [13,14]. However, vastus medialis muscular imbalances could result in compensation and weakness in the contralateral limb, which can decrease the non-dominant extremity's ability to absorb large forces associated with athletic activities [8,16]. Therefore, it was important to investigate the activation times of the vastus medialis and medial hamstring muscles since the activation of the muscle may protect against possible injuries. In addition, the dominant vastus medialis muscle was significantly faster compared to the non-dominant side during stair climbing, especially in the male subjects. Although extensive amounts of research have been conducted in an attempt to identify muscle activation for effective stabilization of the knee, the data is not conclusive and can even be conflicting at times. As a result, it is important to quantify the differences that exist between genders in terms of muscle recruitment and timing of vastus medialis activation.

Our study investigated the effects of anticipation on knee stabilization, as little research has been done in this area. As far as we noticed, there is no study comparing gender and side dominance based on the amplitude of EMG or time delay during repeated stair climbing activities. The results of this study indicated that there is a gender difference in vastus medialis muscle activation since male subjects demonstrated higher overall vastus medialis muscle EMG amplitude values. However, the activation time was longer when male subjects ascended the stairs and shorter while they descended the stairs. Therefore, the delay time of vastus medialis muscle activation during down stair climbing is important to consider for injury prevention and as a rehabilitation strategy. Further randomized, controlled trials are needed to investigate the onset timing and activation patterns of the knee muscles in subjects with knee pain.

## 5. Conclusion

Gender differences in neuromuscular characteristics, including timing of muscle activation, are one of the multiple factors contributing to the difference in injury rates and rehabilitation strategies between men and women. Clinicians need to consider gender differences in vastus medialis EMG activation delay during treatment of patients with knee injuries since functioning of the vastus medialis muscle seems to be a critical factor in the patient's ability to cope with the injury. Our results support the theory that vastus medialis training is necessary to regain good muscle torque. Nevertheless, we believe that this study adds to the evidence base regarding gender differences in neuromuscular mechanisms of the dominant vastus medialis muscle and will inform future research and practice.

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## 6. Conflict of interest statement

No author had an association or financial involvement with any organization or commercial entity having a financial interest in or financial conflict with the subject matter or research presented in the manuscript.


## Acknowledgements

We would like to thank each of the subjects who participated in the study. This research was supported by the Korea University Grant. This material is also the result of work supported in part by the Graduate College of Cleveland State University, Cleveland, Ohio.


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