RESEARCH ARTICLE

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Characteristics of Lower Extremity Muscle Activation in Response to Change in Inclination while Walking on a Treadmill

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ABSTRACT

Treadmill walking is a popular form of exercise that offers many benefits to its users, such as improvements in cardiovascular health and gait patterns. Few research studies have explored muscle activation of various lower extremity joints at different levels of inclination on a treadmill. Therefore, this study aims to further characterize muscle activation during gait in healthy individuals in response to changes in treadmill inclination at a constant speed. Twenty healthy participants (24.5 ± 4.3 years of age) were recruited for this study. Participants were instructed to walk on a treadmill at six different inclines (0%, 3%, 6%, 9%, 12%, and 15%) while maintaining a constant speed of 3.4 mph. Muscle activation of the tibialis anterior (TA), gastrocnemius (GA), gluteus maximus (GMAX), gluteus medius (GMED), vastus medialis (QUADS), and biceps femoris (HS) were collected using surface EMG. There were slight differences in muscle activation between the muscle groups during the various intervals. However, there were no significant differences between muscle groups. The results revealed that the extensor muscles (GA, HS, and GMAX) of the lower extremity showed trends of longer activation periods with an increase in inclination. This study found that as inclination increases, activation of the extensor muscles of the lower extremity also increases while walking on a treadmill. The findings of this study will serve as a baseline for research to compare populations with known gait impairments, such as individuals with HIV, post-stroke, or the elderly, to better understand EMG analysis leading to gait deviations or abnormalities with neuromuscular activation.

Keywords: Activation, Incline, Treadmill, Walking.

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I. INTRODUCTION

Treadmill walking is commonly used in fitness and rehabilitation practices (Kostraba *et al*., 2018). Individuals with various gait impairments secondary to orthopedic or neurological conditions have been found to use treadmill walking as part of their rehabilitation programs (Druzbicki *et al*., 2015; Mehrholz et *al*., 2015; Han & Yun, 2020; Sedaghatnezhad *et al*., 2021). For instance, treadmill training has been performed in individuals' post-stroke, cerebral palsy, and Parkinson's disease to improve gait speed and single-limb support time (Druzbicki *et al*., 2015; Mehrholz *et al*., 2015; Han & Yun, 2020). While treadmill training has been used to improve gait parameters, it has also been shown to improve standing balance (Pirouzi *et al*., 2014; Pereira *et al*., 2020). Pirouzi and colleagues (2014) found that forward walking on a treadmill improved dynamic standing balance, decreased postural sway, and improved gait speed in older adults. Additionally, velocity-dependent treadmill training has been shown to improve dynamic standing balance and reduce the fear of falling in those living with Parkinson's disease (Cakit *et al*., 2007).

The benefits of treadmill walking range from recreational purposes to advantages in rehabilitation settings (Lee & Hidler, 2008). Walking on a treadmill allows for more steps achieved in a shorter duration than overground walking (Moore *et al*., 2010). Increased repetition is helpful for gait assessments or targeting desired locomotion patterns during treatment sessions (Harris-Love *et al*., 2001). Additionally, treadmill velocity (speed) and percent grade of inclination incline can be controlled, which is advantageous for individuals requiring increased repetition and practice during gait in a stable and predictable environment (Seeman *et al*., 2022). Body-weight support systems can also supplement treadmill training by facilitating desired gait patterns for individuals who cannot support their body weight independently (Lee & Hidler, 2008).

Treadmill walking is providing a similar environment to overground walking and sometimes enhanced benefits (Lee & Hidler, 2008). Distinct lower extremity muscle recruitment is an advantage considered between treadmill walking (TM) and overground walking (OW) (Khademi-Kalantari *et al*., 2017). For instance, several studies found that TM produces greater knee extensor and plantar flexion activation than

OW (Prosser *et al*., 201; Lee & Hidler, 2008; Martin & Li, 2016). Lim and Lee (2018) found greater tibialis anterior activation than medial gastrocnemius during OW compared to TM. Nevertheless, the evidence is equivocal on which method produces greater muscle activation.

As mentioned above, one of the advantages of TM is the ability to adjust the percent of inclination and therefore the gait pattern required to adapt to said inclination. Increased inclination requires modifications of gait mechanics to allow adequate toe clearance and increase limb height in preparation for foot contact (Prentice *et al*., 2004). Biomechanical studies have also found that as the inclination increases, extensor moments of the hip, knee, and ankle joints also increase. (Franz & Kram, 2012; Lay *et al*., 2006; Lay *et al*., 2007). However, few studies have investigated differences in muscle activity by inclination/grade, especially when comparing muscles at different joints (Mohammadi & Phadke, 2017; Franz & Kram, 2012; Lay *et al*., 2007). Mohammadi and Phadke (2017) compared the difference in muscle activation between the medial head of the gastrocnemius and the tibialis anterior muscle while walking on a treadmill. Researchers observed an increase in medial gastrocnemius activation compared to the tibialis anterior with an increase in inclination. In addition, increased plantar flexion activation (specifically the gastrocnemius muscle) has been associated with a reduction in the dorsiflexor moment compared to overground walking (Lee & Hilder, 2008). The authors only compared muscle activation between the gastrocnemius and tibialis anterior among three levels of inclination (0, 3, and 6%), and participants were allowed to ambulate at a self-selected speed (Mohammadi & Phadke, 2017). As a result, comparison of muscle activation was limited to one joint, and observation of gait adaptations elsewhere may have been overlooked. Also, having the participant walk at a self-selected speed may have influenced the changes in muscle activity observed with inclination.

Therefore, the current study's aims are three-fold and are designed to further characterize muscle activation during gait in healthy individuals in response to changes in treadmill inclination at a constant speed. This study hypothesizes the following: 1) tibialis anterior will remain active for longer durations compared to the gastrocnemius to allow adequate toe clearance, 2) the quadriceps will demonstrate a longer activation period compared to the hamstrings, as grade/incline increases with concurrent rises in extensor moments, and 3) the gluteus maximus will demonstrate increased activation time with increasing grades/inclination due to an increase in hip extensor moment with inclination. The goal with this inquiry is to expand the current TM literature associated with lower limb muscle adaptation. Identifying lower extremity muscle adaptation will aid gait specialists such as Physical Therapists in developing tailored interventions.

II. METHODS

A. *Ethical Statement*

The Institutional Review Board of Texas Woman’s University’s T. Boone Pickens Institute of Health Sciences – Dallas Center approved this study procedure (Protocol # FY2020-32). Each participant was informed of the procedures, their rights, the risks, and possible adverse effects that could occur during the study. All participants then read and signed an informed consent form.

B. *Participants*

Participants were recruited by word of mouth at Texas Woman’s University in Dallas, TX. Each participant was randomly assigned to one of two groups via the envelope method. Group 1 began at an incline of 0%, while group 2 began at an incline of 15%. The level of inclination at which the participants started was randomly assigned to determine if there were differences in muscle activation secondary to fatigue. The inclusion criteria for this study was that the individual had to be a healthy young adult 20-45 years of age. The exclusion criteria were as follows: 1) history of low back or leg injury within the last six months, 2) currently taking medications that could potentially cause drowsiness or severe balance problems, and 3) women who are pregnant or could potentially be pregnant.

C. *Procedures*

The Institutional Review Board (IRB) approved this study, and informed consent was obtained before screening and testing began. At the initiation of the data collection, demographic information and baseline vitals were collected. Corrective lenses or contacts were also documented during the screening process.

Data were collected using the surface electromyography (EMG) system (Delsys, Inc. Boston, MA). EMG electrodes were placed on the tibialis anterior (TA), gastrocnemius (GA), gluteus maximus (GMAX), gluteus medius (GMED), vastus medialis (QUADS), and biceps femoris (HS) on the dominant leg. A perturbation determined the dominant leg's posterior direction to the anterior shoulder girdle area while testers stood behind participants. Whichever leg was utilized to initiate the stepping strategy for balance recovery following the perturbation was identified as the dominant limb. If needed, areas of the dominant limb were shaved with an electric razor to improve EMG electrode placement and reduce signal interference.

Treadmill protocol: The participant was instructed to begin walking at a speed of 3.0 mph for 20 seconds on a standard treadmill at either 15% grade or 0% grade based on his group placement. The participant was allowed to hold onto handrails if needed. After 20 seconds, the speed was increased to 3.4 mph for the remainder of the protocol. Once a speed of 3.4 mph was achieved, the grade of inclination was adjusted (increased or decreased) by 3% every 20 seconds for 120 seconds (six intervals). The use of handrails was documented by a team member if needed by the participant.

D. Measurements/Outcomes

Muscle activation for six different lower extremity muscles was measured using surface electromyography at different grades of inclination. EMG data analysis was performed on each muscle for the last 10 seconds of each interval to allow for any muscle adaptation that would occur with the adjustment of inclination. Data recorded from the analysis were the time before peak muscle activation, time at peak muscle activation, and time after peak muscle activation for the first peak at 10 seconds and the subsequent peak (second peak).

III. DATA ANALYSIS

This study collected EMG data for six different muscles during six different levels of inclination. The duration of muscle activation was determined by identifying two data points, the difference between time after the peak and time before the peak. The EMG data was placed into the SPSS Data Analysis 25 system for repeated measures ANOVA. For the variables of interest, descriptive statistics and pairwise comparisons were gathered. This study achieved statistical significance with a p-value equal to or less than 0.01.

IV. RESULTS

Table I illustrates the demographic information of the participants. A total of 20 participants participated in this study. The majority of the participants were female and 24.45±4.33 years old. The participants had an average systolic blood pressure (BP) of 114.55±13.55 (mmHg), diastolic BP of 75.30±8.11 (mmHg), resting heart rate of 72.85 ± 11.622 (bpm), and resting oxygen saturation of 98.40±0.60 (SPO2). In addition, participants had an average height of 1.671±0.08 (m), weight of 65.98±10.32 (kg), and body mass index of 23.54±2.68 (kg/m^2). Of the 20 participants, 11 were right-leg-dominant, and nine were left-leg-dominant.

TABLE I: DEMOGRAPHIC DATA OF ALL PARTICIPANTS

Characteristics	Study Participants (n) = 21
Age	24.45 +/- 4.33years
Gender	Male = 4 Female = 16
Height (meters)	M = 1.67 +/- .08
Weight (kg)	M = 65.98 +/- 10.32
BMI (kg/m^2)	23.54+/- 2.68
Blood Pressure	Systolic: 114.55 +/- 13.55 mm Hg Diastolic: 75.30 ± 8.11 mm Hg
Heart Rate (bpm)	72.85 +/-11.62
Sat O$_2$ (%)	98.40 +/- .60
Leg dominance	Right = 11 Left= 9

Table II presents the results of a repeated-measures ANOVA, comparing TA and GA the activation time (duration) at different inclines throughout the walking trial. There were no significant differences between the activation time of the TA and GA muscles with a change in inclination. However, it was noted that the gastrocnemius muscle was active for longer than the TA (Fig. 1).

TABLE II: COMPARISON OF TA VERSUS GA TIME (SECS) OF ACTIVATION DURING DIFFERENT INCLINES

Interval	TA (N=20) Mean and SD	GA (N=20) Mean and SD	P-Value
0% incline	0.9200 ± 0.15811	0.9413 ± 0.1558	1.00
3% incline	0.9353 ± 0.14578	0.9450 ± 0.12644	1.00
6% incline	0.9422 ± 0.19423	0.9647 ± 0.10761	1.00
9% incline	0.9277 ± 0.15925	0.9262 ± 0.19673	1.00
12% incline	0.8813 ± 0.18940	0.9015 ± 0.21801	1.00
15% incline	0.8745 ± 0.17188	0.9083 ± 0.19656	1.00

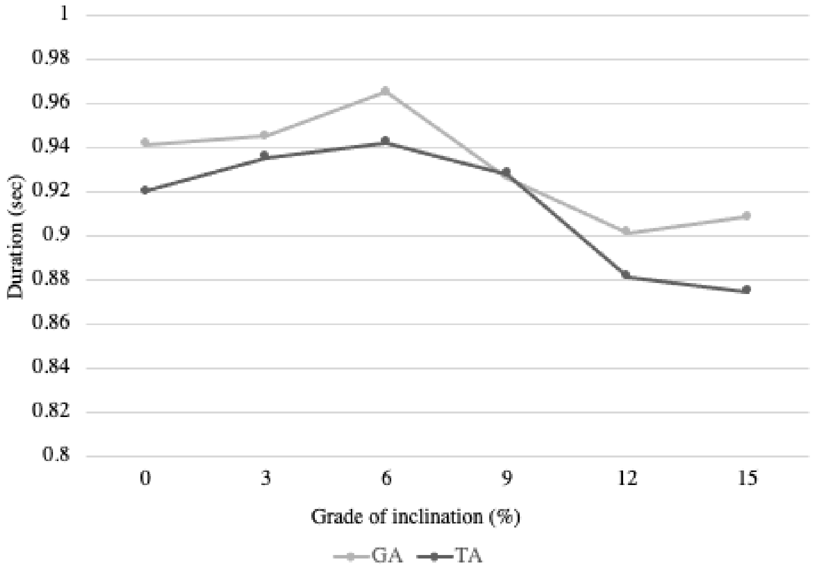

Fig. 1. Comparison of TA vs GA duration by level of inclination.

Table III portrays the results of a repeated-measures ANOVA, where the muscle activation time of the QUADS and HS was compared at different inclines. While there were no significant differences between the activation of the QUADS and HS with change in inclination, as the incline increased, the hamstrings were active longer than the vastus medialis muscle. (Fig. 2).

TABLE III: COMPARISON OF QUADS VERSUS HS TIME (SECS) OF ACTIVATION DURING DIFFERENT INCLINES

Interval	QUADS (N=20) Mean and SD	HS (N=20) Mean and SD	P-Value
0% incline	0.9495 ± 0.17999	0.9228 ± 0.14361	1.00
3% incline	0.8805 ± 0.17505	0.9670 ± 0.11474	1.00
6% incline	0.9685 ± 0.17997	0.9880 ± 0.17378	1.00
9% incline	0.9052 ± 0.21726	0.9692 ± 0.11148	1.00
12% incline	0.9215 ± 0.22918	0.9380 ± 0.12653	1.00
15% incline	0.9437 ± 0.18238	0.9535 ± 0.10063	1.00

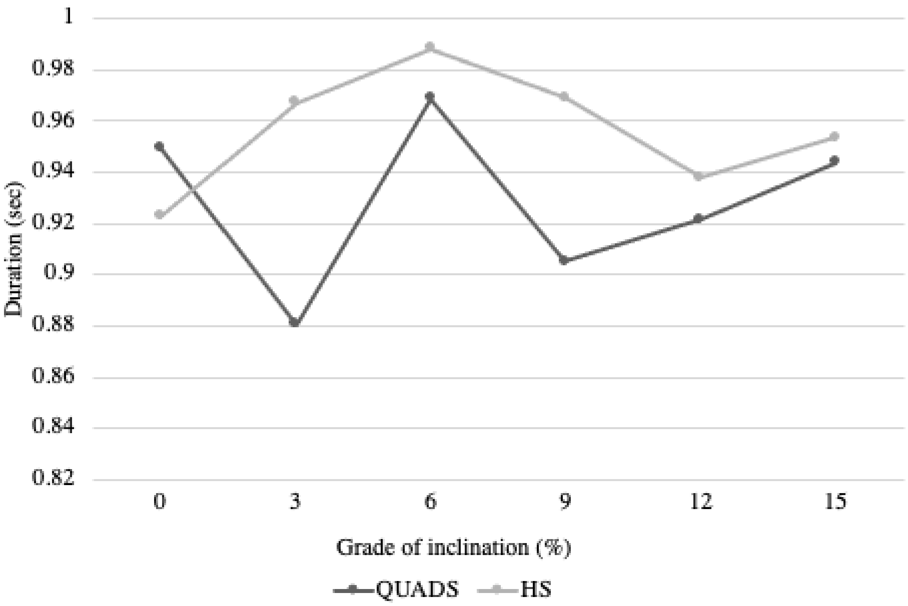

Fig. 2. Comparison of QUADS vs HS duration by level of inclination.

Table IV demonstrates the results of a repeated-measures ANOVA to compare the GMAX and GMED during different levels of inclination. Although no significant variations were found between the activation of the two muscle groups, it was noted that as the incline increased, the GMAX was active longer until the participants reached 12% incline, where the GMED became the leader in duration (Fig. 2).

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TABLE IV: Comparison of GMax versus GMed time (secs) of Activation during Different Inclines

Interval	GMax (N=20) Mean and SD	GMed (N=20) Mean and SD	P-Value
0% incline	0.8786 ± 0.23092	0.8950 ± 0.19474	1.00
3% incline	0.9030 ± 0.22902	0.8907 ± 0.16589	1.00
6% incline	0.9518 ± 0.16182	0.9200 ± 0.19024	1.00
9% incline	0.9102 ± 0.22788	0.8772 ± 0.20595	1.00
12% incline	0.9080 ±0.19405	0.9245 ± 0.21475	1.00
15% incline	0.8605 ± 0.18907	0.9330 ± 0.22156	1.00

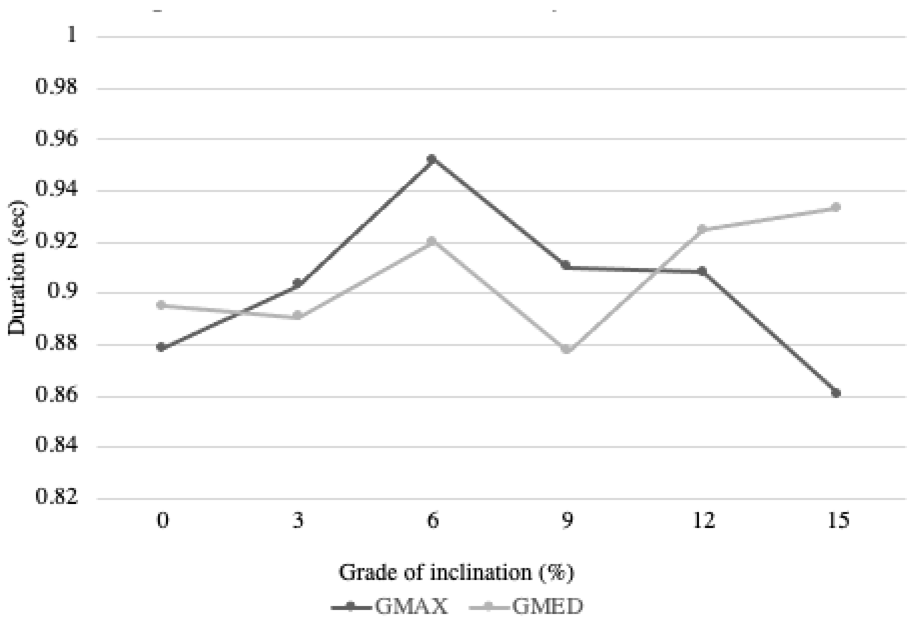

Fig. 3. Comparison of GMax vs GMed duration by level of inclination.

V. Discussion

This study aimed to characterize lower limb muscle activation during gait in healthy individuals in response to changes in treadmill inclination. The study was based on three working hypotheses related to lower limb muscle activation and treadmill inclination. This research illustrates that while there were slight differences in muscle activation between the muscles during the various intervals, there was comparability between muscle groups. The results of the specific hypothesis are reviewed as follows:

This study's first hypothesis stated that as treadmill inclination increases, greater activation of the TA would be seen compared to the GA to allow adequate toe clearance. However, our results showed that the GA was active longer than the TA. Therefore, *we reject our hypothesis.* One explanation for the greater activity of GA could be that GA is generally active during the stance phase of gait, while the TA is mostly active during the swing phase and initial contact (Sutherland, 2001). Therefore, the impact of co-contraction on muscle recruitment during increased inclination must be considered. In addition, several studies have suggested that age influences GA and TA activation in healthy adults (Franz & Kram, 2013; Hortobagyi *et al*., 2009; Monaco *et al*., 2009; Mohammadi & Phadke, 2017). For example, Franz and Kram (2013) found that younger adults showed greater GA activity than older adults with treadmill inclination. Similarly, Hortobagyi *et al*. (2009) found that the amplitude and timing of TA and GA muscle contraction were correlated with age and velocity in healthy adults (Hortobagyi *et al*., 2009). Evidence suggests that increased age is associated with decreased ankle extensor strength, negatively influencing balance and gait mechanics (Monaco *et al*., 2009). Although the main objective of this study was to identify muscle recruitment in lower extremities in young, healthy adults as a means to establish baseline data points, our findings are limited by the age range of the participants. Since the mean age was 24, the current study could not correlate the differences in muscle activation at the ankle between young and older populations. While the evidence supports our findings that the GA is activated longer as the incline increases compared to the TA, future studies should focus on evaluations of muscle activation across different age groups. This comparison will help characterize the co-contraction requirements at the ankle, which influence gait deviations with changes in inclination.

The second hypothesis of this study was that the quadriceps muscle would demonstrate a longer activation period than the hamstrings as grade/inclination increased with concurrent increases in extensor moments. The study found that the QUADS were active longer at a 0% incline than the HS. However, as the incline increased, HS was active for longer. Therefore, *we reject our hypothesis*. Currently, a few EMG studies explore muscle activation when walking on an incline versus level ground (Lay *et al*., 2007; Franz *et al*., 2012). Lay and colleagues (2007) explored the relationships between joint mechanics and muscle activity during level and sloped walking. They found that during up-slope walking, there was an increase in the magnitude and duration of the hip extensor moment (Lay *et al*., 2007). Furthermore, Franz *et al*. (2012) found that hip, knee, and ankle extensor muscle activities during the stance phase of gait progressively increased with steeper hill climbing at all three walking speeds tested: 0.75 m s^{-1}, 1.25 m s^{-1}, and 1.75 m s^{-1} (Franz *et al*., 2012). The increase in extensor moment found in the hip and knee in both studies helps explain the increase in HS found in our study with a change in inclination. However, Franz *et al*., 2012 found additional changes in muscle activation with grade of inclination and greater faster-walking speeds (Franz *et al*., 2012). Therefore, future studies should investigate changes in muscle activation of the QUADS and HS at different speeds with increasing inclination to further complement this limited area of research.

The final hypothesis of this study was that GMAX would demonstrate a greater duration of activation with increasing grade/inclination. This study found that initially (0% grade), the GMED was active longer than the GMAX. However, as inclination increased, the GMAX was active for longer periods until a 12% incline was achieved. Therefore, *we partially accept our hypothesis*. Similar to our study, Jeong *et al*. (2014) compared the muscle activity of the GMED at different levels of inclination during gait and found that the muscle activity of the GMED increased from 0° treadmill inclination to 5°, though the difference was not significant. However, researchers found when the inclination increased from 5° to 10°, the GMED muscle activity significantly decreased. In a normal gait, the GMED plays an essential role in maintaining one's balance and stabilizing the pelvis during the single-leg stance phase (Kim *et al*., 2016). Compared to walking on flat land, walking up an incline requires more balance and postural stability (Jeong *et al*., 2014). One explanation could be related to an inducement of compensatory actions in other body parts to keep the body upright while ambulating forward (Jeong *et al*., 2014). In addition, extensor moments at the hip have also been reported to be four times larger when walking at an incline than walking on level ground (Lay *et al*., 2006). Increases in extensor moments increase extensor muscle activation, explaining why the GMAX was active longer as inclination increased in our study. When attempting to target the GMAX and GMED, clinicians and researchers should be receptive to the level of inclination to appropriately activate the targeted muscle and prevent unwanted activation of other muscles that may contribute to improper gait mechanics. Future research studies should observe these same muscle recruitment strategies in participants walking downhill at various speeds, specifically those with gait deviations, to better understand recruitment strategies within different gait patterns, including level, uphill, and downhill walking.

VI. CONCLUSION

This study aimed to characterize lower extremity muscle activation in response to changes in inclination in healthy young adults. The study's main findings were that the extensor muscles of the lower extremity were generally active for a longer duration as the incline increased. These findings are consistent with previous research suggesting that as incline increases, extensor moments also increase, possibly leading to an increase in extensor muscle activation (Franz *et al*., 2012; Lay *et al*., 2006). However, one limitation of this study was a short warm-up time (15-20 sec) and walking intervals (20 sec), which may have prevented the subjects from settling into a comfortable gait pattern. Giving the participants more time to warm up would allow increased blood flow and stronger contractions of the leg muscles to potentially receive better EMG data. Another limitation of this study was not synchronizing EMG signals to the timing of the gait cycle. Literature illustrates that gait parameters such as gait speed and double limb support changes in response to the diverse surfaces (Rosario MG & Orozco E, 2022). This information would have provided a more specific time frame for the muscle activation and allowed for a better understanding of the co-activation of the muscles at different joints.

Additionally, since this study was performed at a university, the sample size was limited to the age of the students attending. Therefore, the results do not reflect the muscle recruitment strategies across age groups or those with gait deviations due to injury or disease. Nevertheless, a lower limb normative for neuromuscular adaptation during TM inclination was necessary to characterize distinct patterns in this group. This information will serve as a baseline for future studies that compare people with gait deficits and abnormalities with lower extremity neuromuscular activation. In addition, future studies should aim to discover how muscle activation is affected in people with known gait impairments, for whom inclined walking can represent a critical barrier to functional independence.

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