International Journal of Clinical & Biomedical Research
Vol 11, Issue 1, 2026.

Sumathi Publications
Original Article

A comparative study of electromyographic activity of quadriceps muscle in persons with unilateral transtibial amputation using patellar tendon bearing supracondylar endoskeletal prosthesis of the age group 18-60 years with unaffected limb during ascending and descending steps

Ghosh Subhlaxmi, Dolas Vaibhav
Department of Physiotherapy, All India Institute of Physical Medicine and Rehabilitation, Mahalaxmi, Mumbai

Abstract

In transtibial amputees larger strength discrepancies between the intact and the amputated limb contribute to the decreased function of the prosthetic side limb, asymmetrical limb loading and an increased risk of secondary musculoskeletal complications in the intact limb. This study examines the limb loading rate and the difference in limb loading between the intact limb and the amputated limb during ascending and descending step activity using surface electromyography. A cross-sectional observational study was conducted on 30 Transtibial amputees between 18-60 years using PTB- SC Endo skeletal Prosthesis with foot piece. Electromyographic activity of the quadriceps muscle (VMO and VL) of both the limbs was evaluated using surface EMG machine and compared during ascending and descending steps. Statistical Analysis revealed that there is no significant difference in the EMG activity of Quadriceps muscle of the intact and amputated limb during ascending and descending steps. It also found that the Quadriceps muscle recruitment was higher during descending steps than ascending steps along with no significant correlation between the isometric strength and the EMG activity of Quadriceps muscle. There is no significant difference in the electromyographic activity of the quadriceps muscle in persons with unilateral transtibial amputation using patellar tendon bearing supracondylar endoskeletal prosthesis as compared to the unaffected limb during ascending and descending step.

KEYWORDS: Transtibial amputation, EMG activity, Quadriceps muscle, ascending & descending steps.

Introduction

Movement is a fundamental characteristic of human being. Locomotion defines as movement resulting in a change of place or location, enable individual to move from one place to another. Activities such as walking, running, climbing etc. are forms of locomotory movement that require coordinated and efficient movement of the lower limbs. However, these locomotion demands are eventually get compromised in individuals with lower limb loss. Lower limb loss is a result of amputation, a surgical procedure involving removal of part of limb due to disease or trauma. Following a lower limb amputation, an individual is routinely prescribed prosthesis, though which they gradually learn to adapt and relearn his/her pattern of gait [1]. However, it is associated with increased weight bearing, and the overall gait pattern involves an increased loading patterns un the intact extremity [1]. Thus, the lower limb amputations represent an important source of chronic impairments and functional limitations, that adversely impact their returning to activities of daily living, employment status and long-term quality of life [1].

Early identification and modification of potential risk factors are crucial role in preventing the long-term development of secondary health conditions,

Correspondence: **Subhlaxmi Ghosh,** Department of Physiotherapy, All India Institute of Physical Medicine and Rehabilitation, Mahalaxmi, Mumbai. Email: subh.ghosh121@gmail.com

eISSN: 2395-0471
pISSN: 2521-0394

most notably knee osteoarthritis (OA) [1]. In individuals with lower limb amputation, timely risk factors identification and early diagnosis of degenerative conditions, are considered essential for optimizing strategies [2]. To achieve goals it is important to encourage and incorporate therapy programs in rehabilitation which emphasizes on symmetrical weight distribution on the amputated limb as well as the intact limb [3]. It has been found that among long standing below knee amputees' atrophy of thigh muscles and loss of proprioceptive feedback mainly from the ankle joint and relative muscles were significant [3-5].

Previous studies have shown that gait dysfunctions that are observed in prosthetic amputees are largely attributable to abnormal joint loading, which subsequently leads to joint pain and degeneration in the joints over the course of time [6]. Consequently, it has been recognized that residual limb of transtibial amputees (TTA) is less actively involved during the performance of routine tasks such as standing and walking [7]. Furthermore, strength asymmetry between the knee extensors and knee flexors has shown correlate with alterations in ground-reaction forces and joint moment loading rates during TTA gait. [8].

All these studies included various activities of daily living which most importantly included walking [9]. However, amputees walking with prosthesis also need to perform other activities among which maneuvering the stairs require a considerable strength and limb loading symmetry [10]. In light consideration of all the above factors, this study aims to evaluating and comparing the electromyographic activity of the quadriceps muscle of the intact limb and the amputated limb during stair ascent and descent.

Materials and Methods

Research Study design and study setting: Cross sectional observational study was conducted in the Physiotherapy department of tertiary health care center with pre-requisite infrastructure. The study duration was one year.

Study population and sample size: A total of Thirty participants with unilateral transtibial amputation using patellar tendon bearing (PTB-SC) endoskeletal prosthesis were enrolled.

Selection of criteria: Inclusion criteria: An individual in the age group 18-60 years, with unilateral transtibial amputation, using PTB-SC endoskeletal prosthesis for > 3 months, capable of ambulating independently without any assistive aid, with asymptomatic intact limb and classified at functional level- K3 on functional assessment scale.

Exclusion criteria: Individual with any traumatic injuries involving lower extremities (including spine), cardiovascular, respiratory or neurological disorders affecting the performance of the participant; uncontrolled Diabetes mellitus or Hypertension, who underwent any major surgical interventions recently or any surgical history especially of the lower limb affecting function; other medical or surgical conditions affecting the performance of the participant were not included in the study. Presence of neuroma or phantom limb pain or phantom limb sensation, amputees using any walking aid were also excluded.

Subject Withdrawal: participants were free to withdraw at any point of time on any reason.

Operational definitions:

Amputation: surgical or traumatic removal of a limb. It is performed to relieve pain or prevent progression of diseases or excise non-viable tissue, such as malignant or gangrenous ones to avert complications and improve overall functional outcome.

Transtibial amputation (TTA): Below-knee amputation involving the resection of the foot, ankle joint, distal portions of tibia and fibula along with the associated soft-tissue structures. This level preserves the knee joint, thereby improved mobility, energy efficiency, and prosthetic rehabilitation relative to higher level.

Patella Tendon bearing supracondylar socket (PTB-SC): A prosthetic socket design featuing by medial and lateral sidewalls extending above and over the femoral condyles, providing superior mediolateral stability and self-suspension with a metallic shank.

K level functional assessment scale: Also known as Medicare Functional Classification Level (MCFL), is used to evaluates a patient functional capacity five levels (K0-K4). It assesses ability of perform undertake transfers, negotiate low-level environmental obstacles, including curbs and stairs, and tone cadence.

Maximum voluntary isometric contraction: A reliable and valid method for assessing muscle strength and activity to standardize electromyographic (EMG) data. MVIC serve as an standared criterion and serves as key metric in patient evaluation and muscular-activity studies.

Surface electromyography: Non-basic technique electrodes are employing skin overlying a target muscle to record the electrical activity of such a muscle.

Materials: Surface EMG recording machine, Self-Adhesive EMG electrodes, Ethyl alcohol (60%-95%), Cotton, Spring balance (calibration upto 50 Kg), Small suspension sling, Rope, Stepper.

Method:

Study was initiated after approval of ethics committee. Participants were screened for the inclusion and exclusion criteria, explained about the study in the language they understood. And enrolled upon obtaining the written consent. Demographic details were collected.

Placement of the electrodes: Self-adhesive EMG electrodes were used to record the activity of vastus medialis oblique (VMO) and vastus lateralis.

(VL) muscles of the intact limb as follows:

• VMO – 4 cm superior and 3 cm medial to the superomedial patellar border, oriented 55° to the vertical line.

• VLO – 10 cm superior and 6 cm lateral to the superior border, and oriented 15° to the vertical line.

• Ground electrode was placed over thigh.

Maximum voluntary isometric contraction: MVIC was assessed in high sitting (90° knee flexion) using spring balance (max 50kg). Subject was asked to sat on a plinth and was instructed to extend the knee against the resistance. Unaffected and affected both the limbs were tested for 3 trials and the highest amplitude from sEMG was documented and used to normalization.

Step ascending test: Subject was asked to ascend the step and the peak amplitude of the muscle activity was recorded by the surface EMG during stance phase. The subject performed this activity for three trials. Subject ascended the step with the intact limb first and then with the amputated limb each for three setups. A 5-minute rest preceded descent testing. (Fig 1)

Descending step: The same technic used for the descending step. Peak amplitude captured during stance phase (full loading the descending limb). The data obtained was normalized with the MVIC and was used to compare the electromyographic activity of quadriceps muscle from both the limbs during ascending and descending step. The statical comparison was done between intact limb and prosthetic limb during ascent and descent. Formula for normalization of data: Recorded amplitude ×100/ MVIC.

Outcome measures: Isometric strength of Quadriceps muscle (Kgs), Maximum Voulntary Isometric contraction (MVIC) – microvolts μV, Amplitude from the quadriceps muscle activity of intact and amputated limb was recorded using surface EMG (sEMG) and was measured in microvolts(μV) during ascending and descending steps.

RESULTS

Table: 1 shows value of mean and standard deviation (SD) of demographic data viz age, height, weight and BMI of total participants (n=30) with Unilateral Transtibial Amputation using PTB- SC Endo skeletal Prosthesis with foot piece.

Fig 1. Ascending and descending steps

Fig 2. Recording of MVIC and isometric strength of Quadriceps muscle.

	Age (years)	Height (cm)	Weight (Kg)	BMI (Kg/m2)
Mean±SD	41.6 ±10.7	168.7 ±9.5	64.9 ±10.8	23.3±3.3
Min – max	(20-59)			

Table 2 shows values of mean, standard deviation (SD) and median of EMG activity (Normalised values of amplitude %) of quadriceps muscle (VMO and VL) of the intact limb and amputated limb in persons with Unilateral Transtibial Amputation using PTB- SC Endoskeletal Prosthesis with foot piece (n=30) during ascending and descending steps.

Mean ± SD	**Intact Limb Amplitude (%)**		**Amputated Limb Amplitude (%)**	
	VMO	VL	VMO	VL
Ascending steps	73.5 ±37.7	75 ±63.5	65.4 ±32.2	60.8 ±33.5
Descending steps	92.7±48.5	78.5±27.3	83.7 ±32.7	80.3 ±38
Mean ± SD	12.57 ±7.71		7.83 ±6.94	

Table 3 shows values of comparison between EMG activity (Normalised values of amplitude %) of the quadriceps muscle (VMO and VL) of the intact limb and amputated limb in persons with Unilateral Transtibial Amputation using PTB- SC Endoskeletal Prosthesis with foot piece (n= 30) during ascending steps and descending steps using wilcoxon test which is graphically represented in Fig 3 and Fig 4 respectively.

	Ascending steps		Descending steps	
	Intact Limb VMO VS Amputated Limb	Intact Limb VL VS Amputated	Intact Limb VMO VS Amputated	Intact Limb VL VS Amputated
P (two tailed)	0.222	0.330	0.407	0.637
P <0.05	>0.05	>0.05	>0.05	0.05

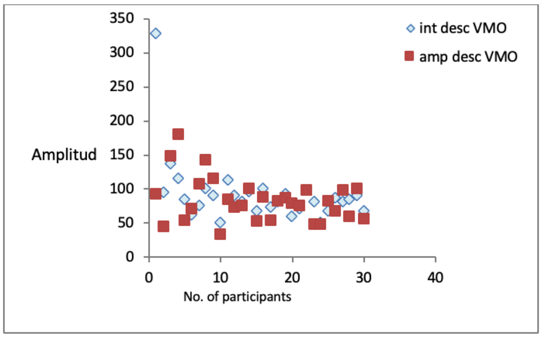

Fig 3. Comparison between EMG activity during ascending steps

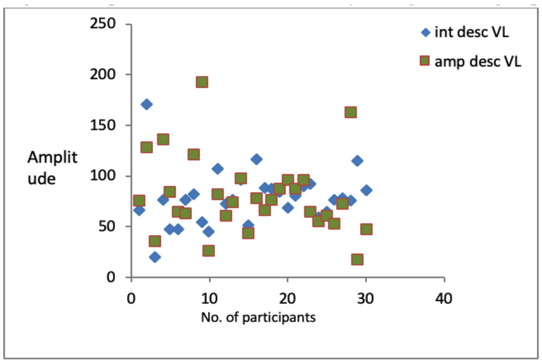

Fig 4. Comparison between EMG activity of Quadriceps during descending steps

Tables 4 shows inferential values of correlation between EMG activity (Normalised values of amplitude %) of the quadriceps muscle (VMO and VL) of the amputated limb in persons with Unilateral Transtibial Amputation using PTB- SC Endoskeletal Prosthesis with foot piece (n=30) during ascending and descending steps with the isometric strength of the quadriceps muscle of the same limb which is graphically represented in Fig 5 and Fig 6 respectively.

	amp iso strength vs. amp asc VMO	amp iso strength vs. amp asc VL	amp iso strength vs. amp desc VMO	amp iso strength vs. amp desc VL
P (two tailed)	0.3698	0.3754	0.5985	0.8546
p<0.05	>0.05	>0.05	>0.05	>0.05
r	0.1698	0.1678	0.1002	-0.03492
Significance	NS	NS	NS	NS

(r- correlation coefficient; S- Statistically significant; NS- Non-Significant Amp- amputated limb; Iso- isometric; asc- ascending; desc- descending)

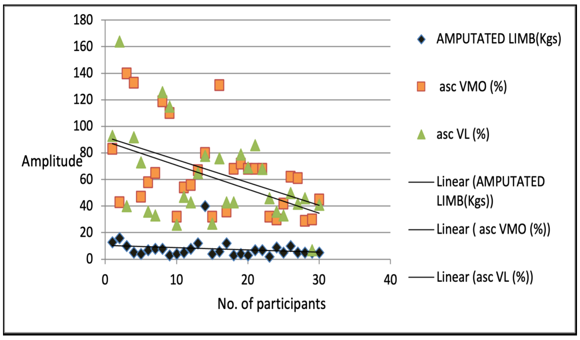

Fig 5. Correlation of EMG activity with isometric strength of amputated limb during ascending steps

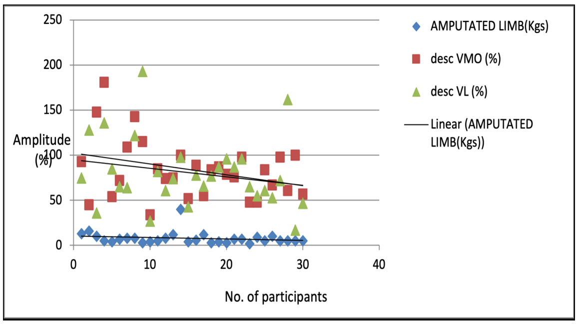

Fig 6. Correlation of EMG activity with isometric strength of amputated limb during descending steps

Table 5 shows Inferential values of correlation between EMG activity (Normalised values of amplitude %) of the quadriceps muscle (VMO and VL) of the intact limb in persons with Unilateral Transtibial Amputation using PTB- SC Endoskeletal Prosthesis with foot piece (n=30) during ascending and descending steps with the isometric strength of the same limb, which is graphically represented in Fig 7 and Fig 8 respectively.

	int iso strength vs. int asc VMO	int iso strength vs. int asc VL	int iso strength vs. int desc VMO	int iso strength vs. int desc VL
P (two tailed)	0.2691	0.3126	0.3505	0.5823
p<0.05	>0.05	>0.05	>0.05	>0.05
r	-0.2084	-0.1908	-0.1766	-0.1046
Significance	NS	NS	NS	NS

(r- correlation coefficient; S- Statistically significant; NS- Non-Significant; int- intact limb; iso- isometric; asc- ascending; desc- descending)

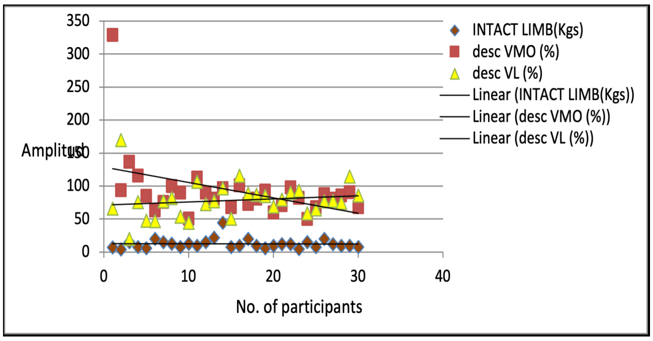

Fig 7. Correlation of EMG activity with isometric strength of intact limb during ascending steps

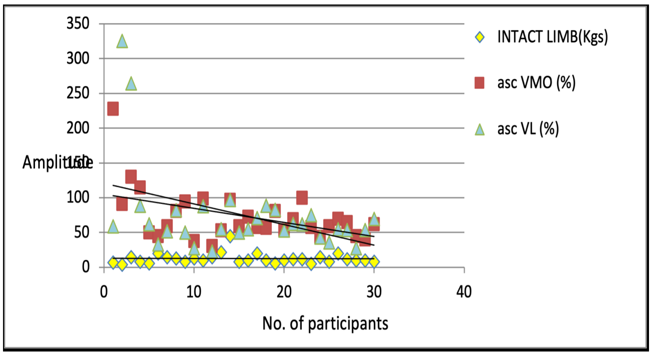

Fig 8. Correlation of EMG activity with isometric strength of intact limb during descending steps

Discussion

This study was conducted on 30 Unilateral Transtibial Amputees using PTB-SC endoskeletal prosthesis with foot piece of the age group 18-60 years to compare the electromyographic activity of quadriceps muscle (VMO and VL) of the intact limb with amputated limb during ascending and descending steps.

Quadriceps have been an important muscle of the lower limb which allow independent walking, helps with stair climbing and enables sit to stand [2]. Hunter et al in their study found that Quadriceps muscle work harder with greater intensity during stair climbing as compared to plain ground walking [10]. These studies were done on healthy individuals; but in individuals with amputation these simple activities including climbing stairs are more challenging [11-14]. The individuals with Transtibial amputation due to loss of proprioceptive feedback from ankle experience difficulty in maintaining balance [15-18]. Many a times a few prosthetic designs do not provide adequate support or flexibility for stair climbing, making it difficult to navigate steps [19]. It has been found that several designs and features such as microprocessor-controlled knees which are advanced prosthetic devices that utilize sensors and algorithms to mimic natural knee movement since these prosthetics adjust providing stability and support [20]. Prosthetic pylon designs with energy storage store energy typically by integrating advanced materials and mechanisms to enhance mobility and reduce energy expenditure[20]. Shock absorption systems, dynamic response feet optimize performance of walking and stair climbing in the transtibial amputees [20, 21]. It has also been found that the remaining muscles work much harder to compensate for the loss, leading to quicker fatigue, especially during prolonged activity [22-24]. Some patients experience pain and discomfort from the prosthetic socket as well as phantom limb pain and neuroma during stair use [24,25].

Environmental factors like poorly maintained or uneven stairs can exacerbate difficulties, increasing the risk of falls during ascending and descending steps [17]. In developing countries where there is mass development with respect to railway and metro networks, accessibility for disabled is a big challenge as there are escalators which are moving platforms where the amputees may find difficulty in stepping over or to climb large flight of stairs. In many places there is lack of facilities like escalator and even lifts, where the only option left is using railway Foot over Bridge manually.

During stair climbing, all the groups of lower limb muscles viz. Rectus femoris, Quadriceps, Gastronemius and Biceps femoris work in synergy for the activity [19]. During maneuvering steps, a strong knee extensor force is required [26-27]. During stair ascent, when the center of mass is forward, Quadriceps is primarily responsible for extending the knee and supporting body weight [19,28]. It concentrically contracts to propel the body upward on to the next step. There is an increased activation of VMO and VL during push off, thus generating forces to overcome gravitational forces and stabilize the knee [19]. In contrast during descending, when the center of mass is backward, the Quadriceps activates eccentrically to control the descent and absorb the impact and prevent rapid knee flexion [10,19, 28].

In Unilateral Transtibial amputation, the person after a few months eventually gets back to his daily routine activity with the use of prosthesis and becomes a community ambulatory. However, during this brief period, it has been observed that the thigh musculature especially the Quadriceps muscle have a high tendency of muscle wasting due to disuse and non-weight bearing on the amputated limb for a long period of time which makes the muscle insufficient and deficient [29]. Cowan et al found that the boundary-value of physiological asymmetry in loading of the limbs in average healthy individuals is 10%

[26]. In unilateral transtibial amputees, when the electromyographic activity of quadriceps muscle of amputated limb with the intact limb in bipedal stance and single-limb stance was assessed and compared it was found that there is increased weight distribution on the intact limb [27]. This asymmetrical loading can be attributed to the absent proprioception from the ankle joint due to co-morbidities such as Diabetes mellitus, Peripheral vascular disease and the prosthetic socket fit [30]. Also, the ground reaction forces play an important role contributing to the kinetics of stair climbing. During ascending step GRFs greater than the body weight is generated against step to propel the body upward to aid the vertical displacement [30]. The forces peak as body weight shifts onto stepping where a strong quadriceps contraction is required [30]. During descending step GRFs increases during initial contact as the body absorbs impact, often exceeding body weight as knee and hip on contralateral side flexes to control descent. This increase in GRF is controlled by the eccentric contraction of Quadriceps as well [30]. Persons with unilateral transtibial amputation also have asymmetries with respect to strength of the lower limb musculature especially the quadriceps muscle where the center of pressure (COP) shifts anterolaterally towards the intact limb. As a result, this will eventually lead to asymmetry in the quadriceps muscle recruitment [5,10,16,30]. These mechanical deviations will be reflected in the gait efficiency of such individuals. Strength asymmetry of the knee extensors and flexors is related to ground reaction and joint moment loading rates in TTA gait [30], which leads to disturbed quadriceps to hamstrings ratio due to which there a reduction in the amplitude derived from the activity of quadriceps muscle [17, 30].

Bolam et al found that the weight bearing functional activities involving the lower limbs have significantly helped in maintenance of the muscle strength and bone mineral density of the bones of lower limbs [30-32].

It was found that the muscle strength was improved by adding weight bearing exercises to quadriceps training program [31,32]. Weight bearing thus helps to maintain the strength of the lower limb muscles particularly the Quadriceps [31, 32]. This was also found by Madhavan et al in his study that Weight-bearing exercises accuracy influences muscle activation strategies of the knee [28, 31].

In this study, we have included unilateral transtibial amputees who have been regular users of prosthesis for more than 3 months and it was found that the asymmetry or difference in quadriceps muscle activation was found not only during stance but also during maneuvering steps both ascending and descending using surface EMG. This difference in recruitment of fibers on the amputated side can also be explained physiologically where it was found that distribution of slow twitch muscle fibers is reduced in amputated limb, and there is a corresponding increase in the distribution of fast twitch muscle fibers which is indicative of low fatigue resistance capacity [29-32]. It was also found that with careful manipulation of exercise variables, one may “potentially” experience fast to slow twitch fiber shift and vice versa [31, 32].

However, the difference in the EMG activity wasn’t significant ($p>0.05$) since the participants were exposed to a brief period of rehabilitation and prosthetic training. Moreover, participants included in this study were the individual’s using prosthesis for more than 3 months. As a result of all these factors the muscles of the amputated limb particularly the quadriceps muscle gets adapted to the prosthesis and the muscle activity recorded is less than the intact limb but not with much difference. It was also found that application of physiotherapy rehabilitation with a suitable prosthesis as early as possible was found to have a significant effect on functional restoration, decrease of energy consumption, improvement of balance, and normalization of gait patterns [29-32]. Kim et al found that there was a lack of significant difference in Vatus lateralis intensity or time of recruitment during ascending and descending steps which again advocates lack of significant difference in the EMG activity [33].

In this comparative study it was also found that EMG activity of the quadriceps muscle was higher during descending steps than during ascending the steps. This can be explained by the GRFs acting on the body along with the body weight [30]. During descending steps, the GRFs often exceeds body weight as knee and hip on contralateral side flexes to control descent [30]. This increase in GRF is controlled by the eccentric contraction of Quadriceps as well which is much higher during ascending step [30]. It was also found in their study that Eccentric activities generally recruit more muscle fibres compared to concentric activities [22, 26]. This is because eccentric contractions can produce greater forces for the same level of effort and often involve higher muscle tension [22-26]. It has also been found that eccentric contractions activate more motor units and lead to increased muscle damage and adaptation, contributing to strength gains [25-27, 30].

In our study we also found that there is no significant correlation between isometric strength and the EMG activity of the Quadriceps muscle since statistically the value of correlation coefficient was negligible ($r<0.3$). Aagaard P et al found that an increase in the muscle strength without corresponding muscle recruitment could indicate improved neuromuscular efficiency, where your nervous system becomes better at activating existing muscle fibres [31,36, 37]. This happens through enhanced coordination or motor unit synchronization leading to stronger contractions without needing to recruit additional fibres [31-33]. It was also found on EMG data that there is no change in maximal neural activation as a result of training even if the strength increases [31-33]. This explains why there was no significant correlation found between isometric strength of the Quadriceps muscle and the muscle recruitment captured as amplitude, since the participants included in this study were the prosthetic users and community ambulators for a period of more than 3 months and had undergone an extensive Rehabilitation program or training program which aided them in functional restoration, improvement of strength and balance and normalization of gait patterns [32].

Conclusion

The current study demonstrates that there is a difference in the EMG activity of Quadriceps muscle of the intact and amputated limb during ascending and descending steps, however the difference was not significant. It was also found that the Quadriceps muscle recruitment was higher during descending steps than ascending steps. The Vastus medialis oblique (VMO) activity was greater than the Vastus lateralis (VL) activity. The correlation between the isometric strength and the EMG activity of Quadriceps (VMO and VL) muscle was found to be negligible.

References

1. Farrokhi S, Mazzone B, Yoder A, Grant K, Wyatt M. A narrative review of the prevalence and risk factors associated with development of knee osteoarthritis after traumatic unilateral lower limb amputation. Mil Med. 2016;181(Suppl 4):38-44.
2. Bordoni B, Varacallo M. Anatomy, bony pelvis and lower limb: thigh quadriceps muscle. StatPearls Publishing; 2023.
3. Lloyd CH, Stanhope SJ, Davis IS, Royer TD. Strength asymmetry and osteoarthritis risk factors in unilateral transtibial amputee gait. Gait Posture. 2010;32(3):296-300.
4. Gailey R, Gaunaurd I, Raya M, Kirk-Sanchez N, Prieto-Sanchez LM, Roach K. Effectiveness of an evidence-based amputee rehabilitation program: a pilot randomized controlled trial. Phys Ther. 2020;100(5):773-787.
5. Pedrinelli A, Saito M, Coelho R, Fontes R, Guarniero R. Comparative study of knee flexor and extensor strength in transtibial amputees. Prosthet Orthot Int. 2002;26:195-205.
6. Powers CM, Boyd L, Fontaine C, Perry J. Lower extremity muscle force and gait in below-knee amputees. Phys Ther. 1996;76:369-377.
7. Isakov E, Burger H, Gregoric M, Marincek C. Stump length related to thigh muscle atrophy and strength in transtibial amputees. Prosthet Orthot Int. 1996;20:96-100.
8. Renstrom P, Grimby G, Larsson E. Thigh muscle strength in below-knee amputees. Scand J Rehabil Med. 1983;9:163-173.
9. Kepple T, Siegel K, Stanhope S. Relative contributions of lower extremity joint moments. Gait Posture. 1997;6:1-8.
10. Sheehy P, Burdett RG, Irrgang JJ, VanSwearingen J. VMO and VL EMG during stair activity. J Orthop Sports Phys Ther. 1998;27(6):423-429.
11. Silverman AK, Neptune RR. Knee joint contact forces in transtibial amputees. J Biomech. 2014;47:2556-2562.
12. Fey NP, Neptune RR. Intersegmental knee loading in below-knee amputees. Clin Biomech. 2012;27(4):409-414.
13. Ebrahimzadeh MH, Hariri S. Long-term outcomes of transtibial amputations. Mil Med. 2009;174(6):593-597.
14. Chihuri S, Wong CK. Fall-related injury in people with limb loss. Inj Epidemiol. 2018;5:1-8.
15. Seyedali M, Czerniecki JM, Morgenroth DC, Hahn ME. Co-contraction patterns in amputee gait. J Neuroeng Rehabil. 2012;9:1-9.
16. Viton JM, Mouchnino L, Mille ML, Cincera M, Delarque A, Pedotti A, et al. Equilibrium and movement control strategies in transtibial amputees. Prosthet Orthot Int. 2000;24(2):108-116.
17. Isakov E, Keren O, Benjuya N. Transtibial amputee gait: EMG and temporal parameters. Prosthet Orthot Int. 2000;24(3):216-220.
18. O'Keefe C. Muscle activation patterns in the transtibial amputee. Melbourne: Monash Rehabilitation Technology Research Unit; 2000.
19. Powers CM, Boyd LA, Torburn L, Perry J. Stair ambulation in transtibial amputees. J Rehabil Res Dev. 1997;34(1):9-18.
20. Alimusaj M, Fradet L, Braatz F, Gerner HJ, Wolf SI. Adaptive ankle-foot system in stair ambulation. Gait Posture. 2009;30(3):356-363.
21. Segal AD, Zelik KE, Klute GK, Morgenroth DC, Hahn ME, Orendurff MS, et al. Energy storage prosthetic foot effects. Hum Mov Sci. 2012;31(4):918-931.
22. Constantin-Teodosiu, D.; Constantin, D. Molecular Mechanisms of Muscle Fatigue. Int. J. Mol. Sci. 2021, 22, 11587. https://doi.org/10.3390/ijms222111587.

23. Wentink EC, Schut VG, Prinsen EC, Rietman JS, Veltink PH. Gait initiation detection in amputees. Gait Posture. 2014;39(1):391-396.

24. Fontes Filho CH, Laett CT, Gavilão UF, Campos JC Jr, Alexandre DJ, Cossich VR, et al. Bodyweight distribution and strength in amputees. Clinics. 2021;76.

25. Tugcu I, Safaz I, Yilmaz B, Göktepe AS, Taskaynatan MA, Yazicioglu K. Muscle strength and bone mineral density in transtibial amputees. Prosthet Orthot Int. 2009;33(4):299-306.

26. Cowan SM, Bennell KL, Hodges PW. Reliability of quadriceps EMG. Phys Ther Sport. 2000;1(4):129-136.

27. Naik D, Dolas V. Quadriceps EMG in unilateral transtibial amputees. Int J Clin Biomed Res. 2021:1-5.

28. Madhavan S, Shields RK. Weight-bearing accuracy and muscle activation. J Neurol Phys Ther. 2007;31(1):12-19.

29. Wilson JM, Loenneke JP, Jo E, Wilson GJ, Zourdos MC, Kim JS. Muscle fiber type shifting with training. J Strength Cond Res. 2012;26(6):1724-1729.

30. Stacoff A, Diezi C, Luder G, Stüssi E, Kramers-de Quervain IA. Ground reaction forces on stairs. Gait Posture. 2005;21(1):24-38.

31. Aagaard P, Bojsen-Møller J, Lundbye-Jensen J. Neuroplasticity and strength training. Exerc Sport Sci Rev. 2020;48(4):151-162.

32. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training. J Appl Physiol. 2002;92(6):2309-2318.

33. Kim H, Song CH. Comparison of the VMO/VL EMG ratio and onset timing of VMO relative to VL in subjects with and without patellofemoral pain syndrome. Journal of Physical Therapy Science. 2012; 24(12):1315-7.