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Gait Analysis of a Subject with Tarsometatarsal Prosthesis

Carlos Diaz Novo[1], Walter Mar Haller[1], Emiliano Alvarez Ruiz[1], Micaela González Castillo[1], Manuel Bárbaro Cuadra[1], Mateo Olivera García[2]

[1]Department of Biomedical Engineering, Universidad Tecnológica del Uruguay, Fray Bentos Rio Negro, Uruguay
[2]Department of Mechatronics Engineering, Universidad Tecnológica del Uruguay, Fray Bentos Rio Negro, Uruguay
Email: carlos.diaz.n@utec.edu.uy

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Abstract

Introduction: Gait analysis of an adult man after trans-metatarsal unilateral amputation is described. **Objective:** Instrumental gait analysis of a subject 15 years after trans-metatarsal unilateral amputation in two footwear conditions: while walking barefoot and with prosthesis. **Materials and Methods:** In a movement analysis laboratory, locomotion studies were carried out at freely chosen walking speed by a 65-year-old subject, obtaining kinematic, kinetic and surface electromyographic data in time and space. Gait analysis was performed using instrumental technologies from a digital ecosystem applying walking protocols. **Results:** When the patient wore the prosthesis, several positive improvements were observed in various aspects of gait. These included enhancements in the base of support, gait speed, and joint range of movements. Additionally, there was a slight improvement in the vertical ground reaction forces pattern, indicating a positive effect of the assistive technology. Furthermore, the use of the prosthesis led to a more organized pattern of muscle activity, which further supports its beneficial impact. However, it is worth noting that some challenges still persisted, particularly regarding stabilizing the body during the double support phase. Despite this difficulty, the overall findings suggest that the use of the prosthesis offers valuable improvements to the patient's gait dynamics. **Conclusions:** After conducting a thorough analysis of the parameters related to the gait of a subject who underwent a trans-metatarsal unilateral amputation fifteen years ago, it was found that the use of prosthesis had a positive impact. This study demonstrated important improvements in some kinematic and kinetic parameters, including muscle activation patterns, indicating an increase in comfort and confidence while utilizing the prosthetic device.

Keywords

Tarsometatarsal Amputation, Prosthesis, Gait, Motion Analysis Laboratory

1. Introduction

Partial foot amputations are often the result of severe infections, vascular disorders, and trauma [1]. One of the diseases that cause the most foot amputations is diabetes (in Uruguay, 60% of all foot amputations are due to diabetes) [2] [3]. Partial foot amputations, such as Tarsometatarsal (TMT) disarticulation, are usually associated with complex gait disorders, including loss of forefoot leverage, a reduction in the plantar loading surface (increasing surface pressure), and loss of pronation and supination, as well as the absence of the propulsive phase (push-off) of the gait cycle [4] [5] [6] [7]. High technologies for human movement analysis need to be applied in order to get an objective idea of the true functional impact of the TMT prosthesis on the gait cycle [8] [9] [10] [11].

The reduction of disorders and asymmetries associated with gait execution plays a vital role in increasing energy efficiency and stability, consequently reducing energy expenditure and the risk of falling [4] [5] [12]. Recent experimental and theoretical findings have demonstrated that an alteration in the dynamics of the metatarsophalangeal joint impacts both the economy of gait [7] [13] and its execution stability [14] [15] [16].

Despite the fact that many aspects of pathological gait have been the subject of scientific inquiry, to the knowledge of the authors, changes in gait patterns after a TMT prosthetic implementation have not been sufficiently documented [12] [17]. For this reason, the purpose of this study is to investigate the gait of an adult man after a TMT unilateral amputation in two footwear conditions: while walking barefoot and with prosthesis.

2. Materials and Methods

The study subject is a 65-year-old patient who has a trans-metatarsal amputation over 15 years ago. At the time of the study, he had a height of 1.75 m and a weight of 83 kg.

A clear and detailed explanation of the project's objectives and procedures was provided to the patient prior to beginning the study. He was informed about the possible risks and benefits of his participation, as well as his rights and responsibilities. Additionally, an informed consent form was given to him, which he had to read and sign to indicate his understanding and willingness to participate in the research.

All procedures were conducted in accordance with the ethical principles for medical research involving subjects stated in the World Medical Association's Declaration of Helsinki. Approval from UTEC was obtained to ensure compliance with the specific requirements of the institution. All questionable aspects of the study were reviewed and approved by an institutional review board.

2.1. Characteristics of the Prosthesis

The patient was wearing a Lisfranc or TMT prosthesis that closely resembled the advanced orthopedic prosthetics provided by MG LATAM [18] (as shown in

Figure 1). The material for that prosthesis is a thermoplastic elastomer type TPE 83A.

2.2. Steps Followed to Carry Out a Gait Analysis of the Patient with and without the TMT Prosthesis

Prior to the experimental data capture sessions of the cross-sectional study, three sessions of 6-minute walks combined with 10 minutes of rest were conducted with the subject wearing the prosthesis. These sessions had a double objective, to promote the muscular warming of the body, and had him walk on a Pro-Form Carbon T7 treadmill, in front of a mirror, to allow him to adapt its gait compensatory mechanics to the prosthesis regimes of use.

After warm-up sessions, 30 trials were conducted along a pathway of 10 m, located in UTEC's movement analysis laboratory, in two footwear conditions: 15 trials while walking barefoot and the rest with prosthesis.

About the middle portion of the pathway, two (2 s) of data relative to the gait cycle was captured to obtain parameters related to kinematics, kinetics, and physiological features of gait cycles for subsequent comparison with a control group of healthy subjects with the same gender, age, anthropometrics and socio-cultural characteristics.

2.3. Gait Analysis in Human Movement Laboratory

A gait analysis was performed using instrumental technologies from the BTS Bioengineering digital ecosystem, which enabled an objective analysis of gait through spatiotemporal kinematics, kinetics, and surface electromyography (sEMG). These technologies included eight surface EMG sensors (FREEEMG 1000®), a wireless inertial sensor (G-WALK®), four force plates for dynamic gait analysis (BTS P-6000®), and a videography system with eight infrared cameras (SMART DX®) combined with passive markers.

3. Results

Gait characteristics observed due to the use of the prosthesis are presented through the kinematics, kinetics and electromyography analysis.

Figure 1. Amputated foot and TMT prosthesis worn by the patient.

3.1. Spatio-Temporal Gait Analysis with and without Prosthesis

For the analysis of the spatio-temporal parameters of the amputee's gait, control values from one group of analogous healthy subjects were taken as reference. Values obtained from both legs of the patient were compared, and possible effects of the prosthesis were revealed (see Figure 2).

Sugiero: The temporal analysis of the gait parameters indicates a longer support time in the healthy limb when the prosthesis is not used (0.81 s), compared to the amputated limb (0.76 s). In both limbs, this time is significantly higher than that shown by the control group (0.63 s), which is related to a walking speed lower than normal (see Figure 2(b)). No benefits resulting from the use of the prosthesis were observed in relation with the reduction of support time.

The swing analysis (Figure 2(c)) shows a clear difference in the time spent by the amputated limb with and without prosthesis (0.48 and 0.51 s respectively), compared to the control group and the healthy limb (0.43 and 0.46 s respectively). Times used by the healthy limb, with and without prosthesis are closer to the control value. A tendency of the amputated limb, with and without prosthesis, to shorten the stance phase is observed.

No differences were observed in the amputee's gait cadence (Figure 2(a)), with the prosthesis (97.8 stps/min) or without it (97.2 stps/min). In both cases, the values are markedly lower than those reported by the control group (113.8 stps/min). This behavior is related to the slow walking speed of the amputee.

The step width (Figure 2(d)) measured with prosthesis (0.120 m) is larger than the control value (0.076 m). Additionally, the higher value was observed when the prosthesis was not used (0.180 m). The disproportional increment of

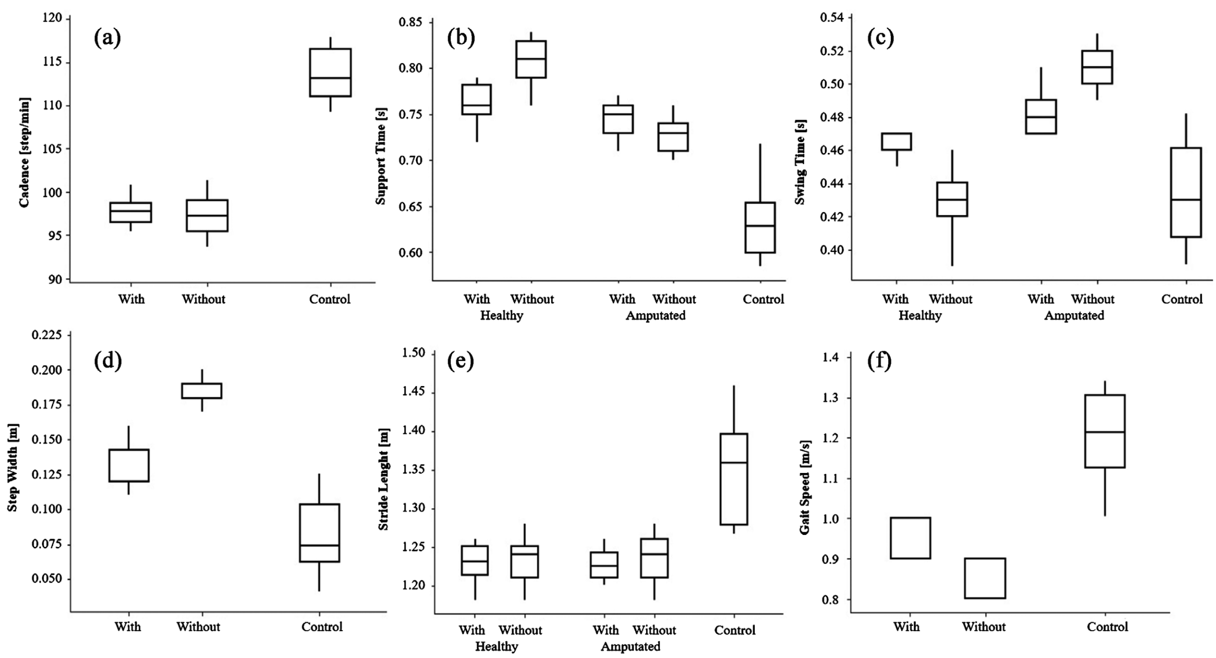

Figure 2. Boxplot of spatiotemporal gait parameters. (a) Cadence, (b) Stance time, (c) Swing time, (d) Step width, (e) Cycle length, and (f) Walking speed.

the base of support is directly associated with instability problems, due to the partial foot amputation. The influence of the prosthesis to reduce the step with is positive but is not enough.

The stride length (Figure 2(e)) is similar (1.03 m) in both legs and does not vary greatly due to the prosthesis (1.15 m). The values are markedly lower than those observed in the control group (1.33 m). This behavior is associated with the amputee's slow gait speed and stability issues.

The amputee's gait speeds (Figure 2(f)), with (0.9 m/s) and without (0.8 m/s) the use of technical assistance, are lower than the normal values (1.21 m/s), with slight increment (0.1 m/s) when the prosthesis is used. This behavior is related to the patient's difficulty to stabilize his body during the double support, caused by the partial amputation of the foot and balance issues in general.

3.2. Kinematics Analysis of Angular Joint Motion with and without Prosthesis

To identify potential effects of the prosthesis in the gait cycle, an analysis of the kinematic range of motions obtained from the hip, knee, and ankle joints in the sagittal plane is performed. Parameters obtained from the amputated and healthy limbs were compared with control values obtained from a control group of analogous healthy subjects (see Figure 3).

In the hip joint (Figure 3(a)), the greatest deviations of (9 deg) are observed for the amputated limb without prosthesis at the end of the support time and beginning of the push off phase of the gait cycle, compared to when it is used.

In the knee joint (Figure 3(b)), differences in the range of motions compared to the ones from the control group were noticed with and without the use of the prosthesis in both limbs. Greatest differences of (20 deg) are associated with the

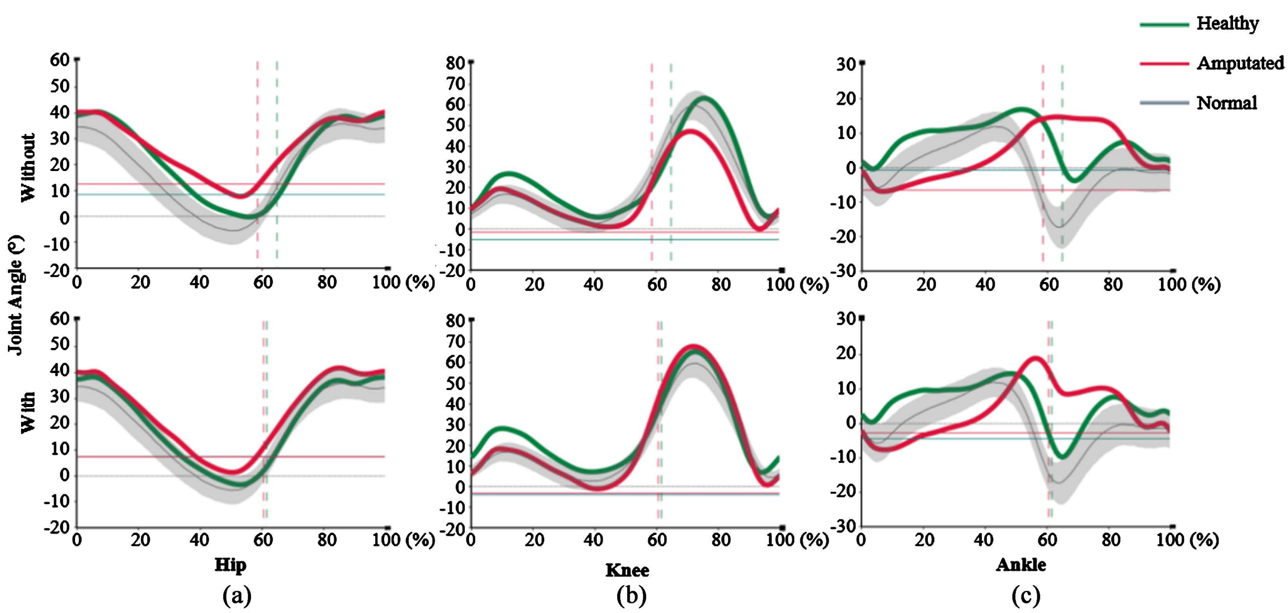

Figure 3. Angular amplitude in the sagittal plane with and without prosthesis of the hip (a), knee (b), and ankle (c) joints as a function of the normalized gait cycle.

flexion of the knee of the amputated limb without prosthesis, during the swing time. In both cases, with and without prosthesis, an abnormal initial flexion of (30 deg) is observed in the knee of the healthy limb, compared to the normal values.

In the analysis of the ankle range of motion (Figure 3(c)), a substantial asymmetry is evident during the swing phase of the gait cycle for both cases. With the patient wearing the prosthesis, there was an early attempt to mimic the normal gait pattern, initiated during the swing time. However, it is important to note that the recorded values were significantly outside the normal range. Normal behavior is observed for the healthy limb, without prosthesis, with a stance time that is slightly longer than 60% of the gait cycle.

3.3. Gait Quality Indicators with and without Prosthesis

General measurements associated with the quality of gait execution obtained with and without prosthesis are presented. Symmetry indexes referring to the kinematic performance of the healthy foot with respect to the amputated are analyzed, exploring possible contributions of the prosthesis to the improvement of gait efficiency.

The analysis of the general gait symmetry index (Figure 4(e)) indicates/reveals/shows a slight improvement of approximately 5% when the patient is walking with the prosthesis, indicating a slight enhancement in gait performance (see Figure 4).

The analysis of gait symmetry indexes in each plane (Figure 4(d)) reveals that the sagittal plane of movement shows the greatest symmetry improvement with

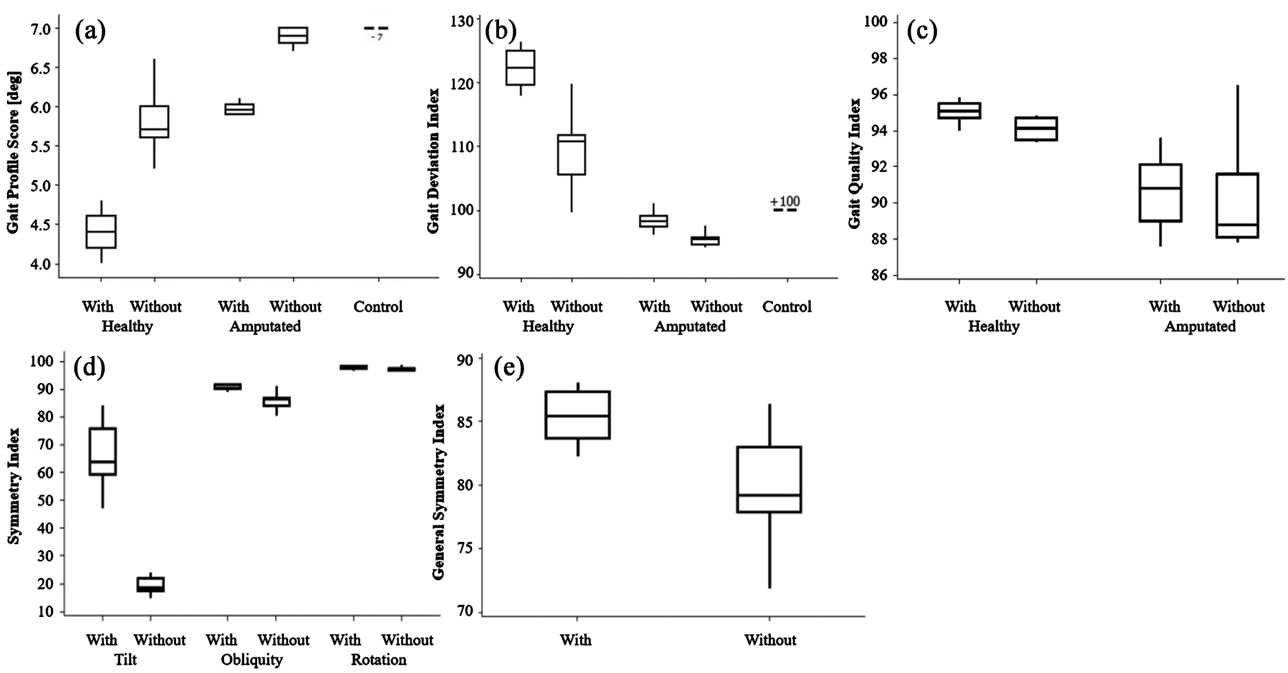

Figure 4. Box plot of gait indexes and scores. (a) Gait profile score, (b) Gait deviation index for both limbs, (c) Gait quality index for both limbs, (d) Symmetric index for both limbs, and (e) General symmetry index.

the prosthesis. The difference of around 55% is remarkable compared to the ones observed for the obliquity and rotation. On the other hand, a slight difference of approximately 5% is noted in the obliquity index measured in the frontal plane due to the use of the prosthesis. Additionally, no difference in the rotational symmetry corresponding to the transverse plane, was observed. Overall, the use of the prosthesis provides benefits for normal and symmetry gait movements in all planes, predominantly in the sagittal plane (Tilt).

In the analysis of gait deviation index (**Figure 4(b)**), the greatest differences are observed for the healthy limb, with a difference of approximately 12%, compared to slight differences (5%) in the amputated limb. The deviation magnitudes in the healthy limb correspond to normal behavior (>100) for this parameter, while the use of the prosthesis brings the deviation closer to the normal range (100) in the amputated limb compared to when it is not used. In the analysis of the gait profile score (**Figure 4(a)**), the healthy limb exhibits the best profile (<7), with greater variability observed with and without the use of the prosthesis. When both limbs use the prosthesis, a proportional difference (0.9 to 1.2 degrees) is observed with and without the prosthesis. The use of the prosthesis contributes to a more normal gait profile in the amputated limb. The analysis of the gait quality index (**Figure 4(c)**) disclosed a slight improvement in gait performance by the amputated limb compared to the healthy limb (approximately 5%). In this case, the prosthesis does not contribute greatly to the improvement in temporal behavior during foot contact and swing. The best performance is observed in the amputated limb when using the prosthesis.

3.4. Kinetics of Gait with and without Prosthesis

From the analysis of the ankle moments in **Figure 5(a)**, it is possible to note that the behavior of the moments of the sound limb correspond to the normal value range throughout the gait cycle in both aspects: amplitude and morphology. However, there is a drastic absence of ankle moment in the amputated leg, which presents a slight increase of approximately 1/4 of the control value at the end of the stance phase due to the use of the prosthesis. This slight contribution to propulsion would be beneficial in reducing gait asymmetries associated with TMT amputation of the foot.

The analysis of ankle power in **Figure 5(b)** could not be different. The TMT amputated foot is unable to generate ankle power losing the chance to take advantage of the ground contact to push off the body sufficiently at the end of the terminal double-leg support subperiod. It is one of the most prevalent gait impairments of this type of amputation, and correlates to a reduced gait speed. The benefit of the prosthesis is almost irrelevant, but modestly sufficient to bring the power generated by the sound limb closer to the range of normal values.

During the analysis of the Ground Reaction Force (GRF) (see **Figure 5(c)**), appreciable differences were found between the one manifested by the sound limb, the amputated one and due to the use of the prosthesis. Overall, the sound

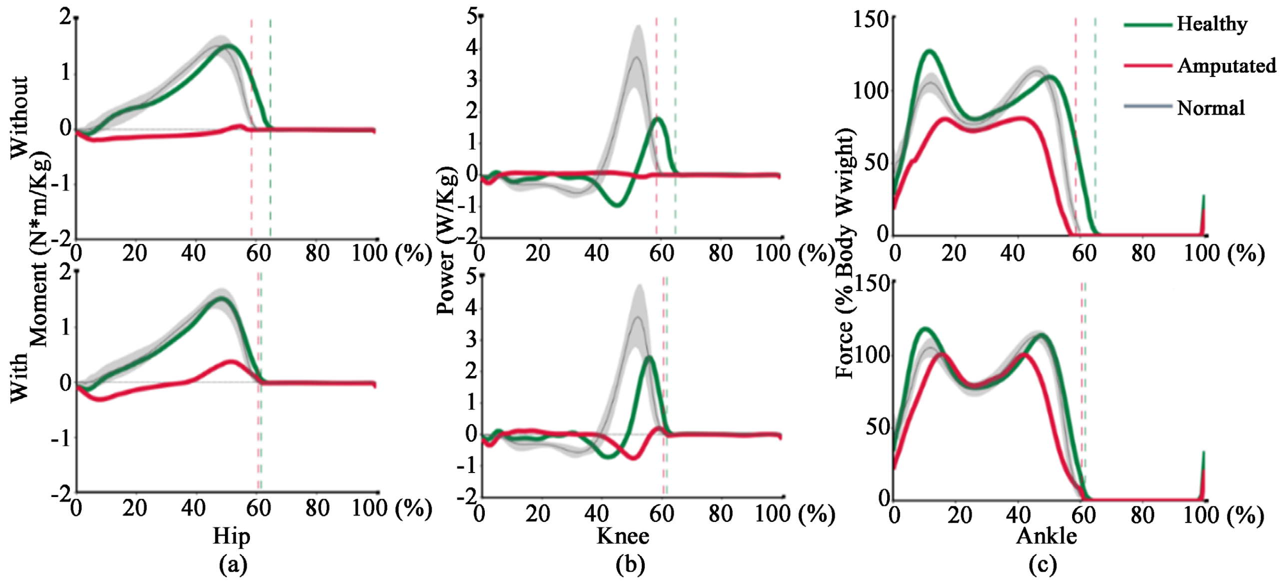

Figure 5. Representation of ankle moment in extension-flexion (a), ankle power generated and absorbed (b), and vertical ground reaction force (c) as a function of the gait cycle with and without prosthesis. Green and red graphics are compared with a control group, in gray, with the same age range as the patient.

leg exhibited a greater similarity to the normal GRF range in both aspects: amplitude and morphology. At the beginning of the foot contact, it was found that the initial peak of GRF in the sound leg is higher than the normal range which could be explained because of a rude transition of the center of pressure from the amputated limb to the sound one during double support subperiod. This effect seems to be attenuated when the prosthesis is used.

GRF associated with the amputated leg without prosthesis showed an atypical morphology, characterized by a plateau instead of the normal pattern shape of a double well. This is because the residual stump is used cautiously by the amputee for support and weight transfer purposes, avoiding propulsion and hard deceleration. However, when the prosthesis is used, a significant improvement in the behavior of the GRF in the amputated leg was observed. It is evident that the patient supports the residual limb with more confidence and relies on the prosthesis to propel the body through the amputated limb, improving the asymmetries caused by his disability.

3.5. Analysis of the Antagonist Muscle Activity in Regard to the Gait Cycle

The EMG recordings from lower limbs principal muscles: Tibial Anterior (TA), Gastrocnemius Lateralis (GL), Rectus Femoris (RF), and Semitendinosus (ST), represented by their mean and standard deviations are plotted with respect to the normal gait cycle. In addition, the EMGs from both limbs, with and without the use of prosthesis, are compared to the normal muscle activation timing of a control group similar to the evaluated subject (see Figure 6).

From the evaluation of antagonist activity at the knee muscles, without the use

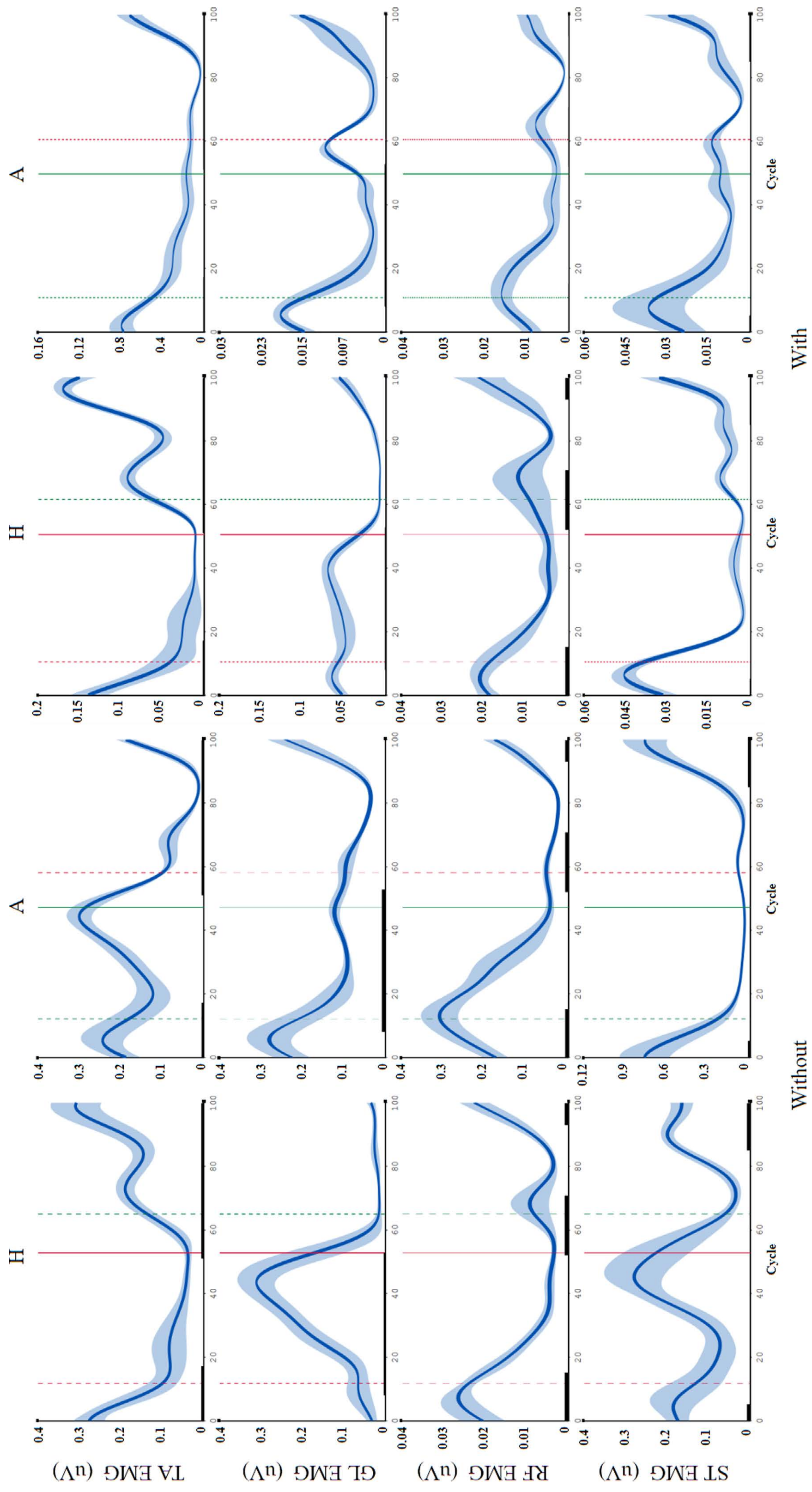

Figure 6. Recording of mean and standard deviation of antagonist superficial muscle activity (EMGs) in thigh and calf, obtained in Tibial Anterior (TA), Gastrocnemius Lateralis (GL), Rectus Femoris (RF), Semitendinosus (ST), without and with prosthesis, in Amputated Limb (A) and Healthy Limb (H).

of the prosthesis, markedly abnormal activity of the ST in the healthy limb is observed at the end of the stance phase. With the use of the prosthesis, the amputated limb's ST EMG replicates a slight repetitive abnormal pattern at the end of the stance. Both behaviors are related to an abnormal compensatory over-propulsion activity in the knee. The rest of the antagonistic activity shows a behavior closer to normal levels.

A similar antagonistic evaluation of the ankle, without the prosthesis, abnormal activity is observed in the amputated limb's TA at the end of the stance phase, combined with a lack of muscular activity in the GL. The activation of the GL is delayed toward the end of the swing phase. In the presence of the prosthesis, the amputated limb exhibits an abnormal behavior of the GL with a marked presence of a biphasic activity. Meanwhile, the healthy limb shows slightly abnormal activity, but more closely follows its corresponding normal pattern for the gait cycle. The rest of the activity corresponds to a normal behavior.

4. Discussion

Enhancing energy efficiency and stability while minimizing the risk of falling heavily relies on mitigating disorders and asymmetries associated with gait performance.

While studies have been published evaluating and describing gait patterns in patients with partial foot amputations, this study focuses on describing variations in gait patterns due to the premature use of a metatarsophalangeal prosthesis. The case study involved an elderly individual with metatarsophalangeal amputation who underwent an experimental gait analysis without any prior training or rehabilitation, utilizing a prosthesis adapted to his disability.

4.1. Kinematic Analysis of Amputee Gait

The analysis of the spatiotemporal parameters, both with and without the prosthesis, together with the comparison to those obtained from a similar control group, revealed a modest positive impact of the prosthesis. It is worth noting that, despite the patient experiencing a slight increase in walking speed and a noticeable reduction in step width due to its use, both improvements fell short of reaching the corresponding normal values observed in the control group. The results indicate an enhanced structural organization of the gait cycle with the prosthesis, particularly during the stance phase, fostering increased confidence in walking and contributing to improved stability and overall performance.

Furthermore, there was an improvement in temporal symmetry between both limbs during support and swing phases, with both durations slightly longer compared to those observed in the control group. These findings suggest that the patient experiences greater comfort and confidence in supporting weight with the prosthesis compared to the bare amputated foot. The slight increase in durations indicates a persistent decrease in walking speed, which is a characteristic of TMT amputation observed in amputees with type 2 diabetes by various authors

[4] [5] [6] [12]. A rehabilitation strategy focused on increasing cadence and step length should aim to restore greater comfort in prosthesis use for the patient, ultimately leading to an increase in walking speed.

4.2. Analysis of the Angular Ranges of Motion

In the absence of the prosthesis during walking, it was observed that the range of angular variations at the hip, knee, and ankle joints decreased noticeably compared to the control group. This observation aligns with findings from studies conducted on patients with type 2 diabetes and partial foot amputation [5]. The prosthesis, by increasing the contact surface at the base of the foot, plays a beneficial role in expanding the angular ranges of motion, particularly in the hip and knee joints.

The excessive initial flexion of the knee in the intact limb, with and without the use of the prosthesis, stands out, which may be related to the abrupt transfer of the Center of Pressure (CoP) during double support instance, from the distal end of the amputated foot to the sound limb, as previously reported [12] [17]. This plantar support dynamics behavior of the TMT amputee can be inferred from the observed increase in vertical forces for the initial heel contact of the intact foot in the analysis of GRF, as shown in **Figure 5(c)**. The increased initial knee flexion during early heel contact may be related to an attempt to dissipate the loads that are abruptly transmitted to the intact limb at the beginning of support.

4.3. Kinetic Improvements in Amputee Gait Due to the Prosthesis

Congruent with TMT-type amputation results reported previously [5], the obtained results reveal a noticeable decrease in power and moment generation through the ankle during the latter part of double support, crucial for propelling the body before the swing phase, due to the loss of transmetatarsal prominences. Interestingly, the prosthesis demonstrates a slightly beneficial effect, characterized by the generation of a small moment and an incipient power generation through the ankle. This assistance is further highlighted in the resulting pattern of GRF, which approaches a more typical double-peak behavior. Particularly, the second peak, directly linked to body propulsion at the end of the stance phase, demonstrates the significance of the prosthesis in enhancing amputee gait. In the absence of the prosthesis, these advantageous effects are not present.

4.4. Surface Electromyography Manifestations Associated with Amputee Gait and the Alteration of Patterns Due to the Prosthesis

From the surface electromyography analysis of the antagonist muscles, an association can be observed between a TMT amputation and the reduction in ankle plantar flexor moments [4] [17]. The underlying cause of this reduction is the diminished capacity of the calf muscles to generate enough power for ankle plantarflexion and produce the necessary ankle torque to facilitate movement of the amputated foot.

No generalized abnormal activity was detected in the summary analysis of EMG of knee and ankle antagonists attributed to the influence of the prosthesis. However, specific areas of newly emerging abnormal muscle activity were observed, particularly near the level of amputation, and were associated with early indications of muscle propulsion and distal joint stabilization, which were evident during the initial and final stages of double support. When comparing the EMGs of the amputee with those of a comparable control group, a more organized pattern of muscle activity was observed with the use of the prosthesis, indicating a slight beneficial effect of the assistive technology, as shown in Figure 7.

5. Conclusions

In order to investigate the potential positive impact of the technical aid prior to patient familiarization, this study analyzed the gait of an adult male with a unilateral TMT amputation in two conditions: walking barefoot and with prosthesis. The research was successfully conducted in a specialized laboratory dedicated to the analysis of human movement.

The analysis of factors related to the time and space of movement revealed a modest but positive effect of the prosthesis, resulting in improvements in walking speed and step width; however, these improvements did not reach the levels observed in the control group. Furthermore, the use of the prosthesis enhanced the structural organization of the gait cycle, particularly during the phase of supporting the body weight, leading to increased confidence, stability, and overall performance. The study also observed an improvement in the synchronization between the movement of both limbs during the phases of support and swing, indicating a greater sense of comfort and confidence when using the prosthesis. Additionally, abnormal muscle activity was observed in specific areas

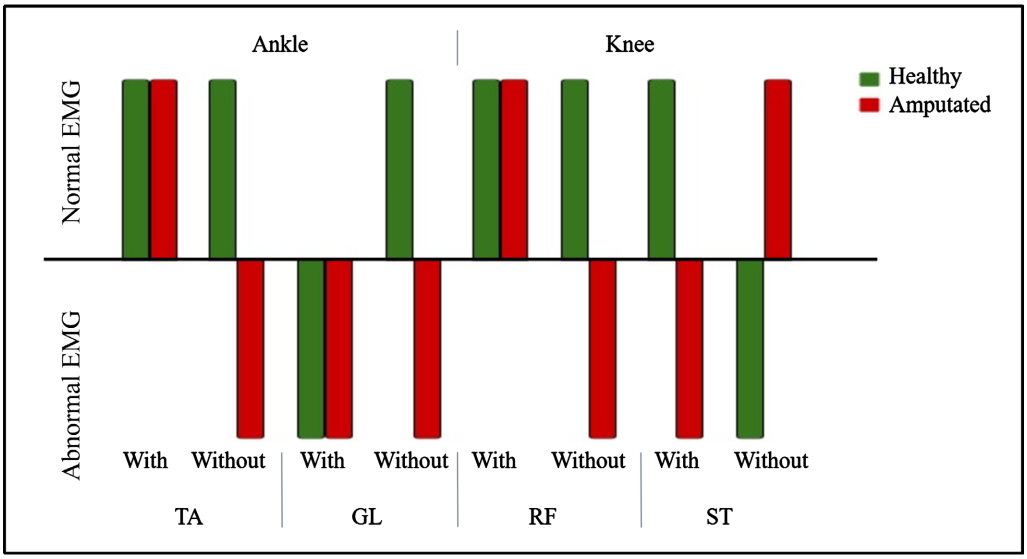

Figure 7. Summarized and encoded (normal and abnormal) activity corresponding to the antagonistic muscle coordination of the ankle (TA-GL) and knee (RF-ST) pairs, in relation to the gait cycle.

near the amputation site, which was associated with early signs of muscle propulsion and stabilization of the joints. When comparing the electromyographic data with the ones obtained in a control group, it was evident that the use of the prosthesis resulted in a more consistent and organized muscle activation pattern, suggesting a slightly positive impact of the prosthesis on gait performance.

Limits Due to the Population Size

Our conclusions are based on a single case study with a 65-year-old participant who had undergone amputation 15 years ago due to traumatic causes. Therefore, it is important to exercise caution when generalizing the findings to other populations.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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