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Effects of arm swing on spatiotemporal characteristics of gait in unilateral transhumeral amputees

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ABSTRACT

Background: Gait is an autonomic process consisting of coordinated movements of the upper extremities, lower extremities, trunk and pelvis. However, researches regarding effects of upper extremity problems on gait parameters are limited.
Research question: The aim of this study was to investigate the effects of arm swing on spatiotemporal characteristics of gait in individuals with unilateral transhumeral amputations.
Methods: A total of 25 unilateral transhumeral amputees and 25 healthy subjects were included. Information on the demographic features of individuals, amputations, and prosthetic devices were recorded. Spatiotemporal characteristics of gait were obtained using the GAITRite electronic walkway, and the arm swing was evaluated with the two video-cameras and analyzed using the Dartfish Pro Suite 7 software.
Results: The groups were similar regarding their age, height and weight. Mean duration from the amputation was 14.91 ± 10.90 years, and the mean weight of the prostheses was 1.44 ± 0.39 kg. Amputees had a less ambulatory arm swing on their amputated sides compared to their intact arms and healthy individuals. When the amputee group was compared to the healthy individuals, their step and stride lengths were shorter and their foot progression angle was higher, their gait velocity and cadence were lower than the healthy group.
Significance: The reduction of arm swing on the amputated side in unilateral transhumeral amputees is thought to be due to (1) use of the contralateral side in functional activities, (2) restriction of shoulder joint movement of socket boundaries and (3) fixed mechanical elbow joint. It has been thought that a decrease in the arm swing during walking may lead to a decrease in step length, stride length, and gait velocity.

1. Introduction

Gait is an autonomic process consisting of coordinated movements of the upper extremities, lower extremities, trunk and pelvis [1]. The role of reciprocal arm swing during walking has been described, and it has been shown that the arm swing has an essential role in increasing the stability by preventing rotational trunk movements, improving balance, and reducing energy consumption [2–4]. It has been postulated that the functional arm swing is a mechanism developed against free vertical moments generated by moving limbs. Moreover, the angular velocity of the arms is equal but opposite to the angular velocity of the body [2]. It has also been stated that in this way, arm torque helps to neutralize lower extremity moments [5]. It has also been reported that upper extremity movements as facilitated by lower extremity movements during regular walking [3] and that the arm/leg cycle frequency ratio was 1/1 [6].

Studies on the effects of upper extremity movement patterns on gait have frequently been conducted regarding problems involving the lower extremities and the trunk. However, studies of upper extremity problems are limited to studies investigating the effects of simulated conditions on walking in healthy population [7–9]. In healthy adults, the restraint of arm swing has been shown to cause changes in the coordination between extremities and cadence, as well as a decrease in stride length, step frequency and gait velocity [8]. Similarly, simulated elbow contracture in healthy subjects showed that the elbow contracture led to a decrease in gait velocity, stride length and single support time, and an increase in double support time [10].

Studies conducted on individuals with cerebral palsy, stroke, and Parkinson's disease showed that decreased arm movement was strongly associated with a reduced gait velocity [10–12]. It has been shown that using verbal stimulation to increase arm swing in individuals with Parkinson's disease improved the gait velocity and stride length [13]. It

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was noted that the amount of arm swing and gait speed in Parkinson's disease were strongly correlated [14].

As can be seen, most of the previous studies concentrated on walking in patients with neurological involvement in both upper and lower extremities [10–14]. The effects of isolated upper extremity orthopaedic problems on walking have not been sufficiently demonstrated. For this reason, our study was designed with the aim of determining whether the arm swing has changed or not and the effects of arm swing on spatiotemporal characteristics of gait in unilateral transhumeral amputees.

2. Methods

2.1. Participants

Patient records of the University Prosthesis and Biomechanics Unit and the Orthopaedics and Rehabilitation Centre were screened and 137 individuals with upper extremity amputations were identified. Thirteen (9.4%) of the identified people did not want to participate in the study, 99 individuals with limb loss were excluded due to not meeting inclusion criteria. Twenty-five participants (study group) of the 137 individuals were recruited for the study. The control group consisted of 25 healthy adults, who had similar demographic characteristics with the study group.

Inclusion criteria for amputees were as follows; having undergone a unilateral transhumeral amputation due to trauma and using a prosthesis for at least six months.

Inclusion criteria for healthy participants were willingness to participate in the study and having similar demographic characteristics with the amputee group.

Demonstrating decreased muscle strength in the lower extremities, having limitations in the upper and the lower limbs during active or passive movements, and having other neurological, orthopaedic or metabolic diseases constituted the exclusion criteria for amputees and healthy participants. Amputees using prostheses with an electronic elbow joint that produces high-level functions were also excluded.

The study was approved by the University Non-interventional Clinical Researches Ethics Board (IRB approval number: GO 14/175). All participants gave written informed consent.

Data on amputations and prostheses, age, height, weight, sex, time since amputation, duration of daily prosthetic usage, and prosthesis weight were recorded. The dominant hand was defined as the one used for writing for control group [15].

2.2. Assessment of gait

2.2.1. Evaluation of spatiotemporal characteristics

Right/left step length, right/left stride length, right/left base of support, right/left foot progression angle, velocity, and cadence were assessed using the GAITRite electronic walkway (CIR System INC. Clifton, NJ 07,012). The data were obtained by pressure-active sensors from the system with 18,432 sensors, at 60–120 Hz [16]. Gait analysis for amputees and healthy subjects was carried out at the participants' self-selected speed with their natural walking. All participants were informed about the details of the evaluation period. Gait analyses of the amputees were utilized while they wore their prostheses.

2.2.2. Assessment of arm swing

Records were done at a speed of 100 fps with the two Basler AcA1300-200uc (Basler AG, Ahrensburg, Germany) high-speed cameras placed at a distance of 2 m from both sides of the GAITRite walkway. Video recordings were performed concurrently with the gait analysis. Acquired video recordings were analyzed by the Dartfish Pro Suite 7 Analysis Software (Dartfish company, Friborg, Switzerland) [17]. Upper extremity joint movements were evaluated in both groups. During the gait, the absolute sum of the maximum flexion and extension angles of the shoulder joint was used for determining the shoulder movement range and expressed as amputated and intact arm swing.

Additional symmetry indexes were calculated for arm swing. The following formula was used to calculate the symmetry index for arm swing:

$$\text{Symmetry Index (SI)} = \frac{|\text{Intact arm swing-Amputated arm swing}|}{0.5x(\text{Intact arm swing+Amputated arm swing})} * 100$$

A symmetry index of 0 equals perfect symmetry [18].

2.3. Data acquisition and processing

Each measurement was utilized by the same investigator to avoid inter-observer related deviations.

In statistical analysis; the amputated side (AS) was compared to the non-dominant side (NS) of the control group and the intact side (IS) was compared to the dominant side (DS) of the control group.

The lower limbs were matched with the upper limbs as amputated side or the intact side in order to overcome the problem of analysis and interpretation of bilateral variables (right/left step length, right/left stride length, right/left foot progression angle, etc.). Also, as no previous data on how the loss of upper extremity affects lower extremity movements was evident, it was considered that the most suitable way to record the data was to take the amputation side of the upper extremity into account. Therefore, bilateral variables in the amputees were coded as “amputated” and “intact” sides according to the amputation side of the upper extremity, and analysed as such.

Data from the participants were analysed by using the SPSS 21.00 software. The mean and standard deviations were described for each group. The Mann Whitney U test was chosen to compare the amputee and control groups. The Wilcoxon’s test was utilized to compare both sides of the amputees and healthy subjects. The Spearman correlation analysis was used to determine whether there was a relationship between the arm swing and spatiotemporal characteristics of gait or not. The p value was set at 0.05 to interpret the results.

3. Results

The mean (± SD) age, height, and weight of the amputee and control groups were 44.16 ± 9.11 years vs. 37.50 ± 7.09 years, 173.75 ± 9.08 cm vs. 175.27 ± 8.44 cm, and 79.91 ± 13.48 kg vs. 83.38 ± 13.20 kg, respectively. There was no statistically significant difference between the groups concerning the age, height, and weight ($p > 0.05$) (Table 1).

Table 1
Participants' demographic characteristics and comparison of groups.

	Min		Max		X ± SD		P
	Amputee n = 25	Control n = 25	Amputee n = 25	Control n = 25	Amputee n = 25	Control n = 25	Amputee-Control
Age(year)	30	22	57	51	44.16 ± 9.11	37.50 ± 7.09	0.065
Height(cm)	157	160	190	192	173.75 ± 9.08	175.27 ± 8.44	0.458
Weight(kg)	56	54	96	100	79.91 ± 13.48	83.38 ± 13.20	0.34

Table 2
Information about amputation and prosthesis.

	Min	Max	X ± SD
Prosthesis weight (kg)	0.64	2	1.44 ± 0.39
Time since amputation (years)	1	33	14.91 ± 10.90
Number of prosthesis (number)	1	9	3.75 ± 3.13

There were 20 men (80%) and 5 women (20%) in the amputee group, and 21 men (84%) and 4 women (16 %) in the control group. In the control group, 19 individuals (76%) were right dominance, and 6 individuals (24%) were left dominance. The average time since amputation was 14.91 ± 10.90 years. It was determined that the individuals started using their first prosthesis no longer than one year following their amputation, and their daily prosthetic usage was at least 8 h a day. The mean (± SD) weight of the prostheses was 1.44 ± 0.39 kg (Table 2). The prosthetics consisted of 40% were body powered controlled, 40% were passive controlled, and 20% were myoelectric prostheses. The elbow joints of all the three prosthetic types were fixed during walking.

Arm swing during gait was 8.59 ± 7.12° in the AS vs. 34.7 ± 14.46° in the IS of the amputee group and 29.64 ± 11.02° in the NS vs. 30.45 ± 14.88° in the DS of the control group (Fig. 1). While there was a statistically significant difference ($p < 0.05$) between the AS and IS arm swing of the amputees, there was no difference between the DS and NS arm swing of healthy subjects ($p > 0.05$). When the arm swing of the amputees and control group were compared, the difference between AS and NS was found to be statistically significant ($p < 0.05$), but there was no difference between IS and DS ($p > 0.05$). There was a significant difference between groups concerning the arm swing symmetry index ($p < 0.05$) (Fig. 1).

Results of the comparison of the amputee and healthy individuals for spatiotemporal characteristics of gait were summarized in Fig. 2. When comparing bilateral parameters, there were statistically significant differences between the step lengths of the AS and IS in the amputees, and it was determined that a longer step was taken with the leg on the same side associated with the amputated arm ($p < 0.05$). There was no difference between the AS and IS regarding other bilateral spatiotemporal characteristics in the amputees ($p > 0.05$). There was a difference between the DS and NS foot progression angle in the bilateral walking parameters of the healthy subjects ($p < 0.05$) (Fig. 2).

When the groups were compared regarding bilateral parameters, it was shown that there was a difference in the stride length in both sides. Foot progression angle between AS and NS; step length between IS and DS were found to be significantly important ($p < 0.05$). There wasn't any significant difference regarding base of support within and between the group comparisons ($p > 0.05$) (Fig. 2).

There was a statistically significant difference between the gait velocity and cadence variables of the amputees and healthy subjects ($p < 0.05$) (Fig. 2).

When the relation of arm swing to spatiotemporal characteristics of gait was examined, it was determined that there was a strong positive correlation between the intact arm swing and bilateral step length, stride length, and gait velocity in the amputee group. There was a strong positive correlation between the amputee arm swing and the intact side foot progression angle as well. On the other hand, there was no relationship between the gait parameters and arm swing in the control group (Table 3).

4. Discussion

The present study investigated the effects of upper extremity amputation and prosthetic usage on arm swing and gait, as a conclusion demonstrated that the arm swing was reduced due to upper extremity loss and prosthetic usage during gait. Unilateral transhumeral amputees had different cadence, gait velocity, step and stride length, foot progression angle when compared to control group.

We observed that unilateral transhumeral amputees had less arm swing in the amputated side at walk. We attributed the reasons for decreased arm swing to; shortening of the extremity due to amputation of the limb, hindering sufficient pendular movement of the arm, use of the intact upper extremity in self-care and activities of daily living (single-handed use), prosthetic socket boundaries restricting shoulder joint movements, and fixed nature of the mechanical elbow joint. In the current study the amputees were fitted with myoelectric or body powered or passive prosthesis due to their requirements. In prosthetic design of the participants, elbow joint movements were not allowed during walking. Also, the shoulder movements were restricted due to the socket boundaries. It was thought that the above reasons led to asymmetries in arm swing in transhumeral amputees. It may be inferred that the decrease in the amputated side arm swing may cause an increase in the symmetry index and thus, the amputees walked with more asymmetric arm swing than the control group.

The inadequate arm swing in the amputees might result in a decrease in the step length of the contralateral lower extremity during gait. Results of the previous studies showed that the decrease in arm swing amplitude caused a decrease in the stride length, step length, and gait velocity [6,8,19] and were consistent with the current results.

The shortening of the intact-side step length in the amputees may have caused a significant difference between groups. On the other hand, the step length of the amputated side was similar to the results of the control group, which probably stemmed from the sufficient swing in the control group. In this case, it may be thought that the unilateral inadequate arm swing will engender a decrease in the step length of the

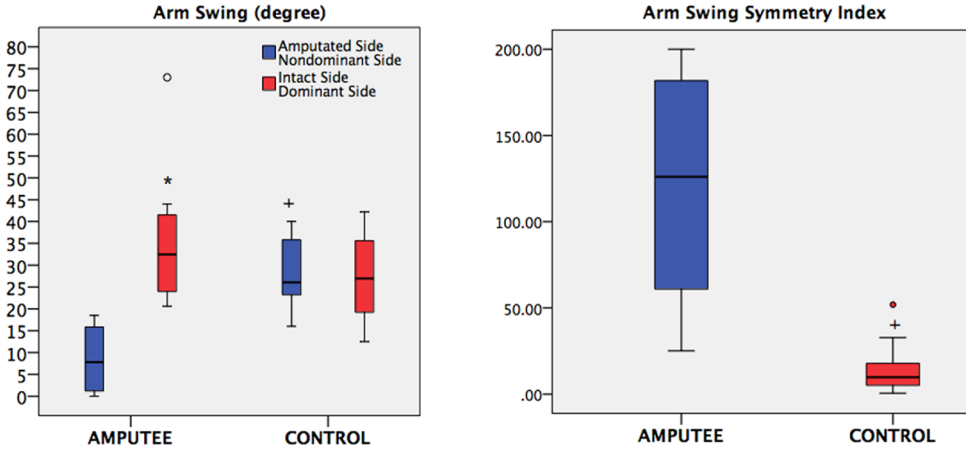

Fig. 1. Box plot graphics of arm swing and symmetry index during walking within and between groups. The box shows the interquartile range (25th to 75 th percentile); the horizontal line indicates the median, and the vertical bars, the range of maximum and minimum value excluding outliers.
AS:Amputated Side, IS:Intact Side, NS:Nondominant Side, Dominant Side
*: $p < 0.05$ significant difference in within-group comparison
+: $p < 0.05$ significant difference in between-group comparison

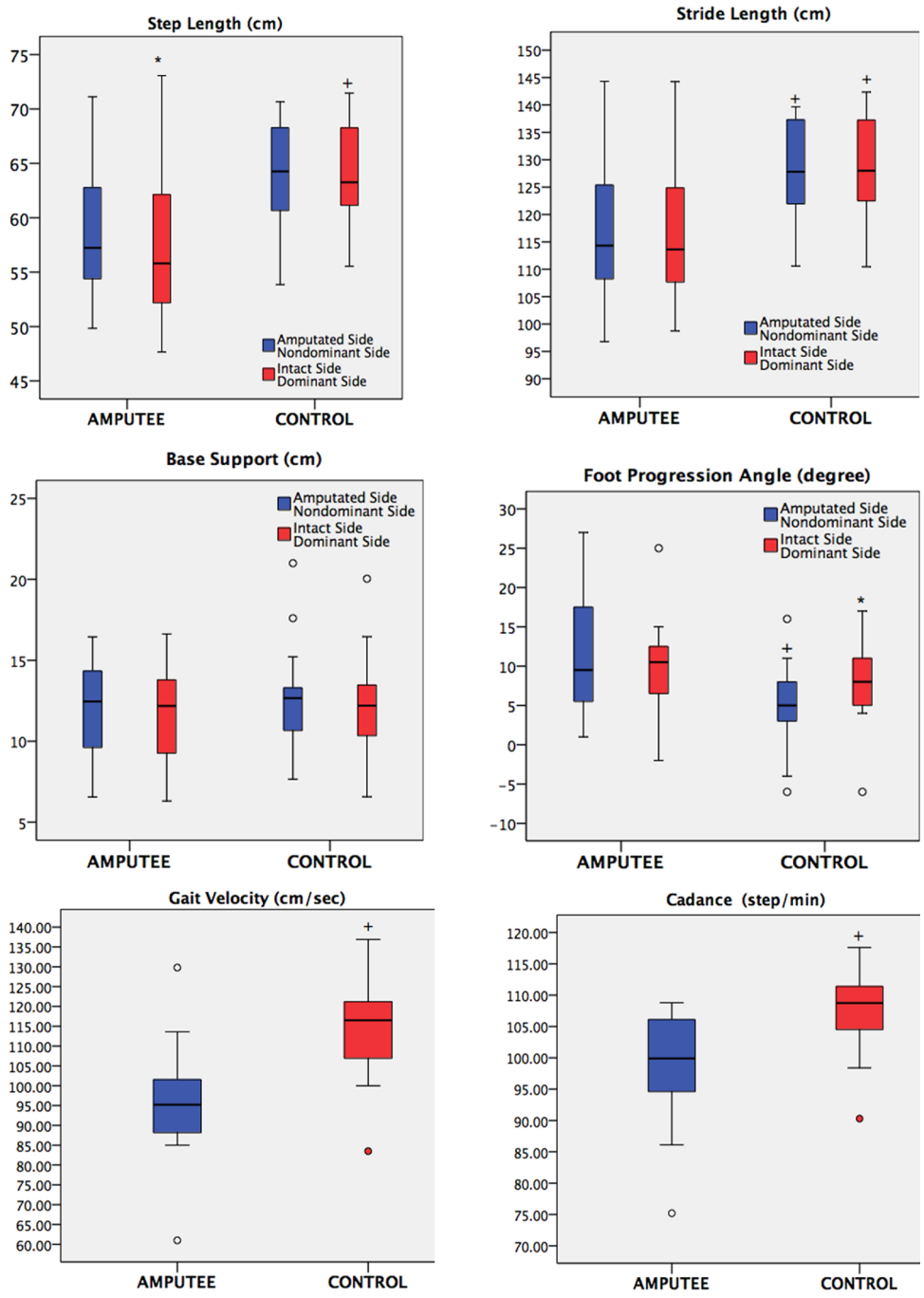

Fig. 2. Box plot graphics of spatio-temporal parameters of gait within and between groups comparison. The box shows the interquartile range (25th to 75 th percentile); the horizontal line indicates the median, and the vertical bars, the range of maximum and minimum value excluding outliers.

lower extremity. Thus, it was also an expected result that the stride lengths of the amputees were different from the control group in both the amputated and the intact side.

According to the present study results, it has been thought that the higher foot progression angle among amputees compared to healthy people was related to the decrease in arm swing in the amputees, which was an important factor in achieving a dynamic equilibrium. Previous study showed that the arm movements have an important role in balance control during walking [20]. It has also been shown that the arm swing contributes to stability following perturbations during walking [4]. It has been postulated that the arm swing helps to stabilize the gait by reducing the angular moments and the ground reaction forces in the vertical direction [2,19]. The reduced arm swing on the amputated side affects dynamic balance negatively. This effect may have been neutralized by increasing the foot progression angle during walking to enlarge the support surface in unilateral transhumeral amputees.

Base of support was considered as an important variable of balance and stability of gait. The lack of difference between the groups in the base of support variable in present study was concordant with the results of the Delabastita et al. study. In that study the arm swing did not affect the mediolateral gait stability [11]. It has been shown that the increase in stability at the mediolateral direction was accompanied by an increase in the arm swing instead of increasing the support surface, and the best stabilization has been shown to occur in cases of excessive arm swing [4]. We thought that the similarities in the base of support between the groups due to the restriction of the arm swing in the

Table 3
Relationship between arm swing and spatiotemporal characteristics of gait.

			Step length		Stride length		Base of support		Foot progression angle		Gait Velocity	Cadance
			AS	IS	AS	IS	AS	IS	AS	IS		
Amputee Group	**Arm swing AS**	**r**	−0.141	−0.337	−0.225	−0.230	−0.389	−0.454	0.417	0.661	−0.224	−0.088
		p	0.663	0.285	0.482	0.473	0.211	0.138	0.178	**0.019***	0.484	0.785
	Arm swing IS	**r**	0.644	0.690	0.681	0.657	0.445	0.315	0.259	−0.047	0.656	0.343
		p	**0.024***	**0.013***	**0.015***	**0.020***	0.147	0.319	0.416	0.885	**0.021***	0.274
			NS	**DS**	**NS**	**DS**	**NS**	**DS**	**NS**	**DS**		
Control Group	**Arm swing NS**	**r**	0.339	0.412	0.350	0.398	−0.029	0.017	0.271	0.399	0.230	−0.080
		p	0.169	0.089	0.155	0.102	0.909	0.946	0.276	0.101	0.359	0.751
	Arm swing DS	**r**	0.232	0.296	0.242	0.282	0.007	0.079	0.303	0.374	0.118	−0.162
		p	0.354	0.234	0.333	0.258	0.979	0.756	0.222	0.126	0.641	0.519

AS: Amputated side, IS: Intact side, NS: Nondominant side, DS: Dominant side.
* $p < 0.05$.

current study may result from the personal adaptation to amputation in over time. Hausdorff *J*. suggested that the negative effects of decreased arm swing on stability among amputees were compensated by walking with shorter steps [21]. Moreover, since amputees walked slower than healthy controls, the need to increase the base of support would have become unnecessary. Studies showed the effect of gait velocity on gait stability, but the relationship between the gait speed on gait stability has not been clearly elucidated [22,23]. When the amputees, whose arm swing was decreased, were compared to the healthy individuals, the results suggested to us that diminished gait velocity in amputees contributed to walking stability.

Gait velocity and cadence of the amputees were slower than the healthy individuals. Decreased gait velocity and cadence resembled the results of previous comparative studies (mostly in patients with musculoskeletal, neurological or orthopaedic problems) which was conducted in healthy people [24,25]. Nevertheless, it should not be overlooked that the results of amputees in present study were within normal limits.

Murray et al. [26] have made detailed description of arm movements in walking and showed that the increase in the amplitude of arm swing was accompanied by an increase in the speed. Also, it can be postulated that the gait velocity decreases due to the decrease of arm swing in the amputees according to results of the current study.

An increase in cadence, gait velocity, and stride length were observed in patients with Parkinson's disease by adding weight to the arm [12]. Plagenhoef et al. [27] showed that the forearm and hand constitute approximately 2.07% of the body weight. The weight of the prostheses that the amputees of the present study used were lighter than a real extremity, which was in line with the results claiming that arm weight is increasing cadence and speed. The prosthesis may be thought of as an additional weight, but actually, the weight of the prosthesis was lighter than the weight of the lost limb and was not similar to the adding weight of the original anatomical structure.

Changes associated with cadence and inter-limb coordination were shown in a study investigating the effects of restricted arm movements on gait in healthy adults [28]. In present study, cadence among amputees with decreased arm swing was found lower than in the control group.

Although the prostheses used by amputees were different, the effect of the prosthesis weight and type on walking were ignored. The fact that the effects of reduced arm swing on the trunk were not assessed may be mentioned as another limitation of the present work. Further studies are required to investigate effects of the different prosthesis on walking parameters of upper limb amputees.

5. Conclusion

This study was conducted to determine the effects of upper extremity amputation, prosthetic usage and arm swing on the spatiotemporal characteristics of gait. As a result, it has been shown that the partial absence of the upper extremity in the unilateral transhumeral amputees and concomitant decrease in arm swing had negatively affects on various gait variables.

In most of the recent studies, the natural swing of the existing limb was increased or decreased by simulation. Simulation of arm swing and evaluation of walking and balance in healthy people does not reflect a real pathological condition, and thus, only short-term effects can be estimated. For this reason, the present study was unique in comparing participants with an actual pathology to a control group. This study will contribute to health professionals dealing with the rehabilitation of amputees concerning planning of assessments and treatment programs.

Conflict of interest statement

All authors stated that there were no financial and personal conflict of interest.

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