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The missing link: How is the phantom limb influenced by prosthesis wearing in people with lower-limb amputation?

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Abstract

Background: Recent therapeutic and technological solutions aim to improve the daily living of people with limb amputation by considering various aspects of the phantom limb, in particular painless phantom sensations (PS) and voluntary phantom movements (VPM).

Objective: Although previous research has explored these phenomena mostly without considering the prosthesis, this study investigates the influence of prosthesis wearing on painless PS, painful PS, and VPM, in people with lower-limb amputation.

Study Design: Cross-sectional study based on semi-directed interviews.

Methods: Semi-directed interviews were conducted with 111 people with major lower-limb amputations. They described their phantom limb without and with the prosthesis, in a static seated position. The influence of the prosthesis wearing on the intensity of painless PS, painful PS, and on VPM ability was classified into 5 categories: disappearance, decrease, modification, increase, and appearance.

Results: Prosthesis wearing leads mostly to an increase of painless PS intensity (44%), a decrease of painful PS intensity (44%), and an improvement of VPM ability (47%). The study also highlights the richness of prosthesis-related changes, including modifications in phantom limb position, shape, and size. The influence of prosthesis wearing on phantom phenomena was not related to the presence of referred sensations, the amputation etiology, the level of amputation, the time since amputation, or the use of medication, but might be related to the pressure applied by the socket on the residual limb.

Conclusions: This study provides valuable information on the influence of the prosthesis on PS and may allow for better consideration of this relationship in the context of research, engineering, and rehabilitation.

Keywords

amputation, rehabilitation, phantom limb, prosthesis, lower limb, painless phantom sensations, phantom limb pain, voluntary phantom movements

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Introduction

Recent innovative projects, especially for people with upper-limb amputation, showed an interest in painless aspects of phantom sensations (PS) for improving myoelectric prosthesis control through voluntary phantom movements[1,2] (VPM, i.e., the ability to voluntarily move the phantom limb, e.g., by executing a flexion/extension of the phantom ankle or toes) or enhancing somatosensory information through residual skin stimulation to evoke painless sensations of the phantom hand.[3,4] However, in people with lower-limb amputation, these phantom phenomena receive very little attention, both in scientific publications and in clinical practice, although they could potentially be useful for improving gait ability.[5,6] Moreover, scientific literature currently investigates the phantom limb in people with lower-limb amputation mostly without the prosthesis.

The investigation of phantom limb phenomena without considering the prosthesis is likely to miss information as (1) the majority of people with lower-limb amputation wear their prosthesis every day, often from morning to evening,[7,8] and (2) there is some evidence in the literature, suggesting that PS characteristics vary with prosthesis. Indeed, wearing the prosthesis was shown to stimulate "postamputation phantom phenomena" in 42% of 122 people with lower-limb amputation surveyed.[9] Then, the prosthesis affected PS of 35% of patients in a study about war veterans that included 1000 participants of whom 740 were amputated of the lower limb.[10] In another study, the wearing

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of a prosthesis was responsible of phantom limb disappearance in 17% of surveyed people with amputation (n = 283, of which 241 were amputated of the lower limb).[11] In addition, "residual limb movement or use of prosthesis" was cited as factors relieving phantom pain in 14 to 18% of 58 participants with amputation caused by vascular pathology (of which 56 were amputated of the lower limb).[12] A recent study also revealed prosthesis-related modifications of the position/shape of the phantom limb, such as telescoping (i.e., shortening of the phantom limb and disappearance of one or more joints), interpreted by the authors as shunning of the prosthesis by the phantom limb.[7] Considering these elements, it is clear that PS need to be specifically considered while wearing the prosthesis, for better scientific understanding of the phantom limb, for adapted development of innovative projects, and for a more holistic management of the phantom limb in rehabilitation context.

Although the existence of an influence of the prosthesis on PS seems to be well established in the few articles mentioned above, it is essential to analyze and characterize more exhaustively this influence. Indeed, the influence of the prosthesis on the phantom limb was studied, either by exclusively focusing on painful PS,[12] or without distinguishing its different aspects[9-11] (i.e., painless PS, painful PS, and VPM), although these are managed differently in rehabilitation care. Also, to the best of our knowledge, studies mostly considered only one type of possible modification of the phantom limb such as decrease in intensity or change in shape, and modification in the capacity of voluntarily moving the phantom limb was never considered. Thus, there is a lack of precision and exhaustivity in the study of prosthesis-related modifications of the phantom limb.

Besides the scientific interest, the understanding of mechanisms underlying the influence of prosthesis wearing on PS could lead to a better anticipation and management of this relationship in rehabilitation context. For instance, the presence of referred sensations (i.e., modification of PS such as intensification of tingling in phantom toes, induced by residual skin stimulation[13,14]) could be related to prosthesis-related modifications of PS because it was recently suggested in a case study.[5] So, the main objective of this study is to characterize the influence of the prosthesis on painless PS, painful PS, and VPM through semi-directed interviews, performed on a large population of people with major lower-limb amputation. Given the important amount of time that people, in particular those with disabilities, spend sitting each day,[15] this study will focus on the prosthesis-related modifications of PS in a static seated position.

Methods

Patients

Patients were followed in 4 french rehabilitation centers: the Chantecler Clinic in Marseille, the University Institute of Readaptation Valmante-Sud in Marseille, the Regional Institute of Readaptation Louis-Pierquin UGECAM NE in Nancy, and the Maguelone Center in Castelnau-le-Lez. The information was collected by medical doctors through semi-directed interviews from late 2017 to late 2022 in the context of follow-up of the patients. This article only involved French-speaking patients, aged ≥18 years, with major acquired unilateral lower-limb amputation. Osseointegrated patients were included. Among the 127 patients interviewed, this study will focus on 111 individuals who had a prosthesis at the time of the interview. Data were pseudonymized before handing them over to the researchers. An ethical approvement was given by each of the 4 rehabilitation centers, and each patient gave informed oral consent to use the collected information for research.

Protocol

The protocol involved a ~1.5-hour semi-directed interview with rapid tests. The entire interview consisted of 5 phases of which the first 3 were performed without wearing the prosthesis and the last 2 with it (Figure 1). These 5 phases were realized with the patients in a seated position. First, patients were asked to describe their painless and painful PS experienced without wearing their prosthesis, whether present during the interview or experienced during the 6 months preceding it. Descriptions included perceived limb parts (e.g., phantom toes, plantar sole, heel) and types of painless and painful sensations (e.g., tingling, simple presence, pressure, electricity). Second, patients were asked to perform VPM of the phantom toes (flexion/extension of all toes and pianoing), ankle (flexion/extension and mediolateral rotation), and knee (flexion/extension, only for people with above-knee amputation). They had to report by verbal feedback whether they could perform each phantom movement, and if so, mimicking them with the intact limb. The appearance of specific muscle contractions in the residual limb confirmed the execution of phantom movements.[16] Third, referred sensations (i.e., modifications of PS evoked by residual limb stimulation) were tested with localized pressure, light brushstroke over 1 cm and light pricking, applied on the residual limb with a dedicated tool (Buck Neurological Hammer; GIMA®). In the case that no referred sensations were found during the interview, but the patient reported referred sensations experienced within the 6 months before the interview, the patient was considered as having referred sensations. Fourth, after sleeve (if they had one) and prosthesis donning, followed by a pause of 2 minutes (to ignore potential transient changes in PS after the donning of the prosthesis), patients described painless and painful PS in comparison with the nonprosthetic condition. Fifth, as in the nonprosthetic condition, patients were asked to perform VPM, this time with the prosthesis, and reported if, and how, the ability to realize each movement was modified by the prosthesis relative to phase 2.

Description of the influence of prosthesis wearing on PS and VPM

The intensity modifications of both painless and painful PS, as well as the modifications in the ability (i.e., possibility or facility) to perform VPM while wearing the prosthesis, were categorized into

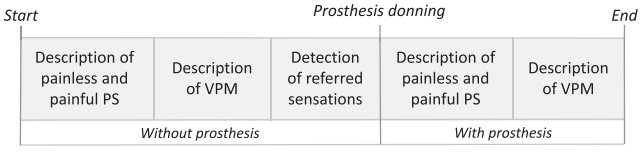

Figure 1. Schematic description of the 5 phases of the protocol. PS, phantom sensations; VPM, voluntary phantom movements.

Table 1. Sex, etiology of amputation, level of amputation, and time since amputation reported as a percentage of the 111 participants.

	Percentage of participants (n = 111)
Sex	
Male	80
Female	20
Etiology of amputation	
Trauma	43
Vascular disease	26
Infection	18
Tumor	8
Diabetes	5
Level of amputation	
Transtibial	44
Gritti	3
Transfemoral	50
Hip disarticulation	3
Time since amputation	
1–6 months	35
6 months to 2 years	23
2–5 years	11
More than 5 years	31

5 terms. Four of them were used when the intensity of all parts of the phantom limb, or the ability of performing all VPM, was influenced in the same way by the prosthesis, i.e., disappeared, decreased, increased, or appeared. The terms "disappeared" and "appeared" describe the case where PS are no longer perceived with the prosthesis or are perceived only with the prosthesis, and where the ability to perform VPM is no longer possible with the prosthesis or is only possible with the prosthesis. The terms "decrease" and "increase" describe a change in PS intensity (decreased or increased) or of ease in performing VPM (more difficult or easier). The fifth term, "modify," was used in the case of a complex association of the other 4 terms, for example, when the intensity of a part of the phantom limb was influenced differently from the others, or when a movement became more difficult or impossible while another became easier. Besides the intensity of PS and the VPM ability, other elements were considered, such as the transition from one type of sensation to another (e.g., tingling to pressure), a change in the position of a phantom segment, or a change in the shape/size of the phantom limb. We specify that this study investigated the influence of PS induced by wearing the prosthesis at rest and not by performing an activity with the prosthesis such as walking.

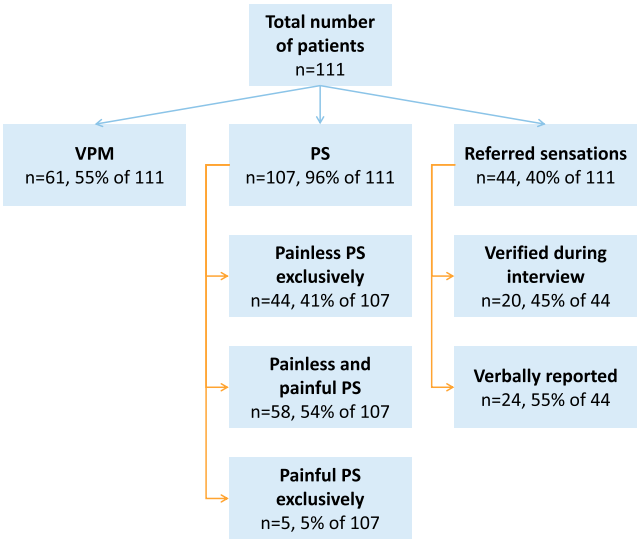

Figure 2. Prevalence of phantom limb phenomena (i.e., PS, VPM, and referred sensations) in the sample of 111 patients. In each category (rectangle), the data are presented by the number of patients (n) and the percentage it represents of a given total number of patients (e.g., n = 40, 50% of 80). The blue arrows indicate the possibility of the same patient belonging to the different categories (having PS, VPM, and/or referred sensations), whereas the orange arrows indicate an "of which," i.e., an exclusive belonging to only one of the categories designated by the arrows for PS, and for referred sensations. PS, phantom sensations; VPM, voluntary phantom movements.

Data analysis

A code was assigned to each patient before data processing. This code is used in this article in the form "Px" (with "x" being a number) when certain testimonials are quoted. The obtained information was entered in detail in a spreadsheet and coded if necessary (e.g., note 1 if the patient had PS without the prosthesis or 0 if he/she does not; note 1+ if painful PS intensity was increased by the prosthesis). Demographic information (i.e., sex, age, time since amputation, etiology of amputation, and level of amputation) was added to the database by doctors, on the basis of patient files. All percentage results have been rounded to the closest integer.

Table 2. Percentages of patients whose painless PS and painful PS intensity as well as VPM ability were influenced by prosthesis wearing, in a static seated position.

	No. of patients whose sensations were influenced by prosthesis wearing (percentage)
Painless PS exclusively (n = 44)	15 out of 44 (34%)
Painful PS exclusively (n = 5)	0 out of 5
Painful and painless PS (n = 58)	
With only painless PS influenced	17 out of 58 (29%)
With only painful PS influenced	7 out of 58 (12%)
With painless and painful PS influenced	9 out of 58 (16%)
VPM (n = 61)	15 out of 61 (25%)

The percentages are expressed according to the total number of patients having PS and/or VPM and having a prosthesis (i.e., 44 for painless PS exclusively, 5 for painful PS exclusively, 58 for painful and painless PS, and 61 for VPM).
PS, phantom sensations; VPM, voluntary phantom movements.

Statistics

Statistical tests were performed on RStudio software (4.0.3). Pearson's chi-squared tests were performed to investigate the relationship between the influence of prosthesis wearing on painless PS (it was not possible for painful PS and VPM as the number of patients for whom these phenomena were influenced by the wearing of prostheses was too low) and various demographic variables or the presence of referred sensations. The significance level for all tests was set at 0.05.

Results

Demographic information

This study included 111 patients, with a median age at the time of interview of 57 years (range = 18–79; interquartile range = 21) and a median time since amputation of 16 months (range = 1–687; interquartile range = 73). Table 1 shows the main demographic information. The majority of patients were male. Amputations were primarily due to trauma, vascular pathology, or infection. Other causes were tumor and diabetes. Amputation levels were transtibial and transfemoral, with some hip disarticulations and Gritti amputations. None of the patients with a socket had a special one (e.g., subischiatic socket for people with transfemoral amputation or flexible socket). Four patients had an osseointegration, all after a traumatic transfemoral amputation. Thirty-five percent of the patients took medication to avoid or reduce residual or phantom limb pain at the time of the interview.

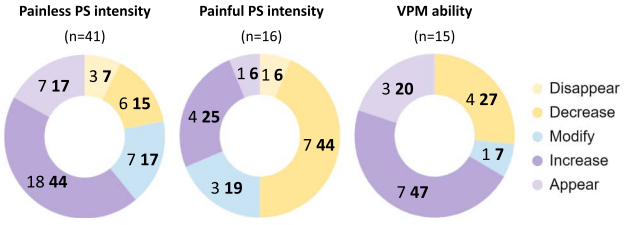

Figure 3. Type of influence of the wearing of the prosthesis on PS and VPM. Number of patients and percentage of patients (in bold) whose painless PS intensity (on the left), painful PS intensity (in the middle), and ability to voluntarily mobilize the phantom limb (i.e., possibility or facility of mobilization; on the right) were modified by wearing a prosthesis in a seated position. The change induced by the prosthesis on PS intensity or the VPM ability could be a disappearance (light yellow), a decrease (yellow), a modification (i.e., a complex combination of different variations of intensity or VPM ability, in blue), an increase (purple), or an appearance (light purple). The total number of patients per category indicated above each circle is the number of patients for whom painless PS, painful PS, or VPM were influenced by prosthesis wearing. The percentages shown in the right-hand circle do not exactly sum to 100% because of rounding. PS, phantom sensations; VPM, voluntary phantom movements.

Prevalence of phantom phenomena without prosthesis

Figure 2 resumes the following information. Among the 111 patients, 96% had PS. Of these patients, 41% had exclusively painless PS, 5% had exclusively painful PS, and 54% had painless and painful PS. Of the patients with painless PS, 31% had them permanently. Of the patients with painful PS, 3% had them permanently. Voluntary phantom movements were present in 55% of all patients. Of the entire group of 111 patients, 40% had referred sensations when the residual limb was stimulated, half of which were found during the interview. The other half were triggered by global stimulation (e.g., massage and contact of a large part of the residual limb with a surface), which was not tested during the interview but reported by patients as experienced within the 6 months before the interview. The 4 patients with osseointegration had painless PS through tingling, and 2 of them (P25 and P53) also had painful PS. P41 and P53 also had VPM and referred sensations, the latter evoked by massage for P41 and by tactile stimulation of the skin around the abutment for P53.

Influence of prosthesis wearing on PS and VPM

The percentage of patients whose PS and VPM were influenced by prosthesis wearing is presented in Table 2. The type of influence of prosthesis wearing on PS and VPM is detailed in Figure 3. Among the 102 patients with painless PS, 40% had their painless PS influenced by the prosthesis (n = 41), which mostly increased their intensity (for 18 patients, i.e., 44% of these 41 patients, as can be seen in Figure 3). Among the 63 patients with painful PS, 25% had their painful PS influenced by wearing a prosthesis (n = 16), which mainly reduced their intensity (for 7 patients, i.e., 44% of these 16 patients). Among the 61 patients with VPM, 25% had their ability to move the phantom limb influenced by prosthesis wearing (n = 15), mostly facilitating it (for 7 patients, i.e., 47% of these 15 patients). None of the 4 patients with osseointegration had any

influence of the prosthesis on their PS or VPM. Finally, although the influence of the sleeve was not studied, 7 patients spontaneously mentioned the influence of sleeve wearing on their painless PS.

The influence of prosthesis wearing on PS in a seated position is developed through some testimonials in this paragraph. Wearing the prosthesis can change the position and the size of the phantom limb. For example, P1 and P54 reported that without the prosthesis, the phantom foot was closer to the residual limb than for the intact limb, but when they put on their prosthesis, the phantom foot "went down into the prosthetic foot." P43 said that his phantom foot became larger when he put on his prosthesis and that the sensations were also more "precise." For P116, his phantom heel, absent without prosthesis, appeared when he put on his prosthesis. P61 explained that when she contracted her residual limb in the socket, her phantom calf appeared, whereas she did not feel it without wearing the prosthesis, even when contracting her residual limb. P91 explained that he felt like his ankle was "twisted" if the socket was poorly fitted. P53 even reported a contradictory influence of prosthesis wearing on his VPM by saying that the prosthesis restricted the phantom knee flexion and extension but facilitated the phantom ankle flexion and extension (this patient is included in the "modify" category in the right-hand circle in Figure 3).

Factors underlying the relation between prosthesis and painless PS

All the statistical tests were nonsignificant. There was no relationship between the fact that prosthesis influenced painless PS and (1) the detected or reported presence of referred sensations ($X = 0.19$, $p > 0.66$), (2) the etiology of the amputation ($X = 0.49$, $p > 0.78$), (3) the level of amputation ($X = 0.25$, $p > 0.61$), (4) the elapsed time between amputation and interview ($X = 4.13$, $p > 0.12$), and (5) the use of medication to reduce pain ($X = 0.26$, $p > 0.60$).

Discussion

The results showed that prosthesis, even in a seated static condition, can have various consequences on PS and VPM. Prosthesis wearing can induce a complete appearance or disappearance of PS or VPM, but for most patients, the changes were more subtle, with a tendency toward an increase in the intensity of painless PS, a decrease in the intensity of painful PS, and a facilitation of VPM. We also observed more complex influences with changes in the position/shape of the phantom limb, or with certain parts of the phantom limb being influenced differently from other parts. The current results do not show the cleavage of phantom shunning or tolerance of the prosthesis that has been described previously,[7] but rather diverse and patient-dependent modifications. Given the variety of potential modifications of the phantom limb induced by the prosthesis, it seems important to carefully analyze this relationship for each patient to help them to better understand their own sensations and improve the integration of this phenomenon into the rehabilitation process. An understanding of the mechanisms underlying prosthesis-related modifications of the phantom limb may even offer goal-directed modulations of PS.

Several elements suggest that prosthesis-related modifications of the phantom limb could be explained by pressure applied to the residual limb through the prosthetic socket. Indeed, in this study, patients reported that wearing the sleeve alone, inducing a diffuse and global pressure over the whole of the residual limb, had an influence on PS, although the prosthesis was not worn. Also, for one patient in this study, contraction of the residual limb muscles inside the socket, thereby increasing the pressure applied onto the residual limb, was found to modify PS, which was not the case when the same contraction was performed without the socket being worn. Moreover, the 4 osseointegrated patients did not have modifications of PS when wearing their prosthesis, which might be related to the fact that no pressure was applied on the residual limb. In coherence with these elements, other evidences have been reported in the literature. Indeed, a recent case study showed that a well-targeted modification of the prosthetic socket led to a modulation of the PS at rest and when walking.[5] Also, a relationship was found between having referred sensations and the incorporation of the prosthesis into the body schema.[11] Moreover, ill-fitting of the prosthesis was reported as a factor increasing PS in a few people with lower-limb amputation.[17] Overall, these elements clearly suggest that the prosthesis-PS relationship is at least partly driven by pressure applied by the prosthesis on the residual limb. The design and fitting of prosthetic sockets can, therefore, have an impact on the phantom limb, and we believe this should no longer be overlooked in the rehabilitation process of people with lower-limb amputation.

The possibility that other elements may contribute to the influence of prosthesis wearing on PS cannot be excluded. For example, a transient modification of the body schema of the lost limb may occur when the prosthetic lower limb is present. Such transient modifications of the body schema have already been reported in the literature, for example, with the "rubber foot illusion,"[18] in which participants have the illusion that a rubber foot belongs to them (the experiment was originally performed on the upper limb and was known as the "rubber hand illusion"[19]). In this study, the visual information designating the lower limb as "complete" could have been partly responsible for the modifications in the body schema and the corresponding sensations, related to this lower limb. This idea refers to the mechanisms underlying the mirror therapy technique.[20] Although the absence of prosthesis-related modifications of PS in the 4 osseointegrated patients does not support this hypothesis, it cannot be rejected, especially given the limited number of studies performed on this subject.

This study has some limitations. First, it is unclear to what extent the pain relief medication may have led to an underestimation of painful PS and maybe of painless PS and VPM. Second, the occurrence of referred sensations may have been underestimated because of the lack of diversity in the stimuli applied on the residual limb during the interview. Indeed, other types of stimulation (e.g., global contact, electrical, vibration, and thermic) have not been tested in this study during detection of referred sensations. This limitation may explain why the statistical test for relation between the presence of referred sensations and the influence of prosthesis on painless PS was not significant. Third, we do not exclude the possibility that other factors, such as the type of prosthetic socket or foot, may have an influence on the prosthesis-related

modifications of PS because of the potential implication of different mechanical stimulations applied to the residual limb and a modification of visual aspects of the prosthesis. Yet, we could not assess this, given that all our patients had a similar type of socket and that access to prosthetic foot type information for each patient was not possible. Fourth, although our sample size of 111 patients seems sufficient for an exploratory study based on semi-directed interviews (see Refs. 9,21-23 for comparison, with sample sizes of 122, 101, 73, and 29 participants, respectively), it would have been interesting to have more patients whose painful PS or VPM were influenced by prosthesis wearing, as this would have enabled us to perform statistical tests as it was performed for potential factors that could influence the relationship between painless PS and prosthesis wearing. Fifth, the present work did not use a quantitative method to assess PS and VPM, because quantitative methods, such as general rating of the intensity of PS between 0 and 10, sometimes cause difficulties for patients because the phantom limb is frequently made up of several parts, each with its own intensity. Moreover, a qualitative method was well suited to an exploratory study such as ours. We encourage through the use of quantitative tools in future studies on the subject to elaborate on the characterization of the relationship between the prosthesis and the phantom limb with particular attention to the richness and complexity of the phantom limb. Finally, this study only explores the relationship between the wearing of the prosthesis and the phantom limb in static and seated condition, so it will certainly be interesting to study in detail the influence of using a prosthesis on PS, in a dynamic situation such as walking or running, as it was partly realized in a recent case study.[5]

In conclusion, this study provides new insights into the relationship between phantom limb and prosthesis. The rich and mostly positive influence of the prosthesis on the phantom limb can have important implications in the clinical context, especially in the design and adaptation of the socket. We encourage further scientific exploration of the underlying mechanisms of this relationship, as well as its characterization, particularly through quantitative assessment of PS and VPM, and during dynamic activities such as walking.

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Declaration of conflicting interest

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Supplemental material

No supplemental digital content is available in this article.

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