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Impact of Gait-Synchronized Vibrotactile Sensory Feedback on Gait in Lower Limb Amputees

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Abstract: Background: Research on sensory feedback systems for prosthetic devices aims to enhance sensory capabilities to better meet user needs. Feedback systems for lower limb amputees (LLA) have been shown to reduce cognitive efforts, metabolic cost and phantom limb pain. This study evaluated the effect of a non-invasive, gait-synchronized, vibrotactile feedback system (VTFS) on the gait parameters of LLA. Methods: Four stimulators applied vibrotactile stimulation to the thigh of LLA during walking, corresponding to four pressure sensors located at the fore- and hindfoot embedded in a sock worn on the prosthetic foot. Standardized gait tests, such as the Timed "Up and Go" Test (TUG), the Four Square Step Test (FSST), the 10 Meter Walk Test (10 MWT) and the 2 Minute Walk Test (2 MWT), were performed to assess the risk of falling, coordination, walking speed and endurance before and after intervention. Results: After an average of 61.5 days using the VTFS, gait stability (TUG) improved significantly. Coordination (FSST) improved in 36% of subjects, while 45% showed a clinically relevant increase in gait speed (10 MWT). Conclusions: The results suggest an improved gait performance in the cohort. Though FSST lacked statistical significance, a *p*-value near 0.05 indicates a trend toward meaningful improvement. Notably, the participant with Targeted Sensory Reinnervation demonstrated the most favorable outcomes.

Keywords: amputation; lower extremity; sensory feedback; prostheses; human–machine interfaces; vibrotactile feedback

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1. Introduction

Available lower limb high-tech prosthetic devices currently do not provide natural sensory information on movements or ground characteristics, which might explain the unphysiological walking patterns with the prosthetic leg [1–4]. Several studies have shown that sensory feedback from the remaining extremity reduces the risk of falling, cognitive efforts, metabolic cost and fatigue of normal physical activity as well as phantom limb pain [1,3–14]. The key qualities that users require from such sensory systems are for them to elicit sensations of touch or proprioception as naturally as possible by delivering complex signals to the nervous system that would be produced by skin, muscle, and joint receptors [15–18].

Sensory feedback systems can be divided into two major groups: non-invasive and invasive/implantable devices. While invasive systems (e.g., implantable neural electrodes) can restore homology and somatotopy of the sensation, which enhance the acceptance and use of the prosthetic device [5], they lack biocompatibility and authenticity, posing high

risks due to invasiveness [17]. The major advantage of non-invasive feedback devices is that they stimulate the body externally, usually through the skin, eliminating the risks associated with invasiveness or surgery. However, without surgical augmentation (e.g., Targeted Sensory Reinnervation) these devices are not able to restore somatotopy of the sensation [17]. Since addressing the skin of the missing limb is not possible post-amputation, cutaneous stimulation must be applied to alternative body sites. Establishing an association between this cutaneous stimulation and the amputated limb generally requires intensive training with the feedback system—a process known as "sensory remapping" [17]. Additionally, non-invasive devices typically transmit sensory information through a single sensory modality (e.g., pressure, vibration or electrical stimulation), lacking authenticity and thus failing to restore sensory homology.

Several studies have evaluated the effect of different non-invasive sensory feedback systems on healthy subjects and amputee patients, including mechanotactile [19–23], vibrotactile [14,20,24–30] and electrotactile feedback [13,27,31,32]. For vibrotactile feedback, however, most studies have focused on upper limb prosthetics [20,24–27,29] or have examined static effects in lower limb amputees, such as improved standing balance and postural control [14], rather than its effects on dynamic tasks like gait [30]. Even though sensory feedback is the subject of the research of numerous prosthetic research groups, no feedback system has yet become established in everyday use or availability [15,17]. Herein, we investigate the effect of a supplementary feedback system that encodes real-time pressure during walking into vibrotactile stimulation of the residual limb's skin.

2. Materials and Methods

2.1. Study Design

The conducted study was a prospective interventional longitudinal study. Data collection took place as part of the routine care for amputees within an amputation-specialized outpatient clinic. The study was approved by the local Ethics Committee of the Hannover Medical School.

2.2. Inclusion and Exclusion Criteria

Subjects with the following amputation levels of the lower extremity were included in the study: below-knee amputation (BKA), knee disarticulation (KD), above-knee amputation (AKA). The exclusion criteria were an existing pregnancy, the inability to walk and stand safely on the prosthesis, age under 18 years and the inability to provide an informed consent independently. The subject's consent was documented in a written declaration of consent.

2.3. Vibrotactile Sensory Feedback System

For vibrotactile stimulation, we used a non-invasive, microprocessor-controlled, gait-synchronized, vibrotactile feedback system (Suralis®, Saphenus Medical Technology GmbH, Baden, Austria). The system features a set of four sensors implemented into a sleeve to be worn over the fitted prosthetic foot. The transmitter unit and the actuator unit of the system are compatible with any commercially available prosthetic setup. The sensors detect pressure at the heel, the lateral forefoot area, the medial forefoot area and at the great toe (see Figure 1). These sensors can record information about the weightbearing of the different foot parts as well as the rolling behavior of the prosthetic foot and can wirelessly transmit this information to the actuator unit through the transmitter unit (Bluetooth technology).

The actuator unit comprises a receiver and an elastic leg cuff containing four embedded vibration elements, with one element allocated to each sensor area of the sock (see Figure 1). The vibration elements oscillate with amplitudes of 60 to 120 Hz, and the latency between sensor ground contact and triggering of vibration on the stump is less than 100 ms.

Figure 1. System components of the herein used vibrotactile feedback system (VTFS): (1) actuator unit, (2) transmitter unit, (3) sensor sock, (4) four pressure sensors at the heel, lateral midfoot area, medial midfoot area and big toe, (5) elastic leg cuff with the embedded vibration actuators (marked in red), (6) single vibration actuator (Copyright Saphenus Medical Technology GmbH).

Thresholds for stimulation (0–100%) as well as vibration strength (0–100%) and duration (0–2.55 s) are adjustable via an App (see Figure 2). The stimulation site within this study was the skin of the lateral thigh of the injured leg. For subjects with a very short AKA residuum, it may be necessary to stimulate the contralateral healthy thigh.

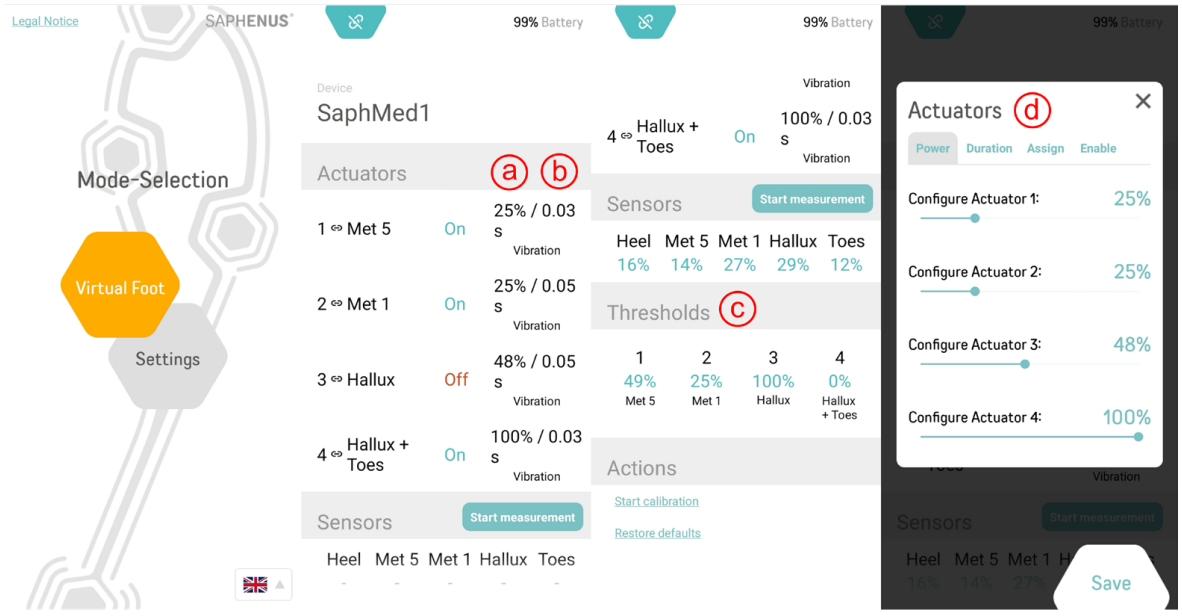

Figure 2. User interface: An App displays the ranges of intensity (**a**), duration (**b**), and threshold (**c**) of the vibrotactile stimulation, which can be adjusted (**d**). The accompanying visual representations provide insight into the parameter settings of the vibrotactile feedback system (Copyright Saphenus Medical Technology GmbH).

2.4. Procedure

The included subjects received thorough instruction on the vibrotactile feedback system (VTFS) and were provided with the option to adjust it using the corresponding mobile application. Threshold, vibration strength, and vibration duration were individualized. To calibrate the feedback system properly, no pressure was applied to the sensors by placing the prosthetic foot, donned in the sensory sock, in the shoe without putting any weight on it. When setting the vibration thresholds of the sensors, we asked the subject to indicate when the stimulation was just perceptible (30–50%). Vibration duration was set at the standard setting of 0.75 s. All subjects were subjected to an elastic leg cuff embracing four vibrotactile actuators as depicted in Figures 1 and 3 and underwent a test run to verify its functionality.

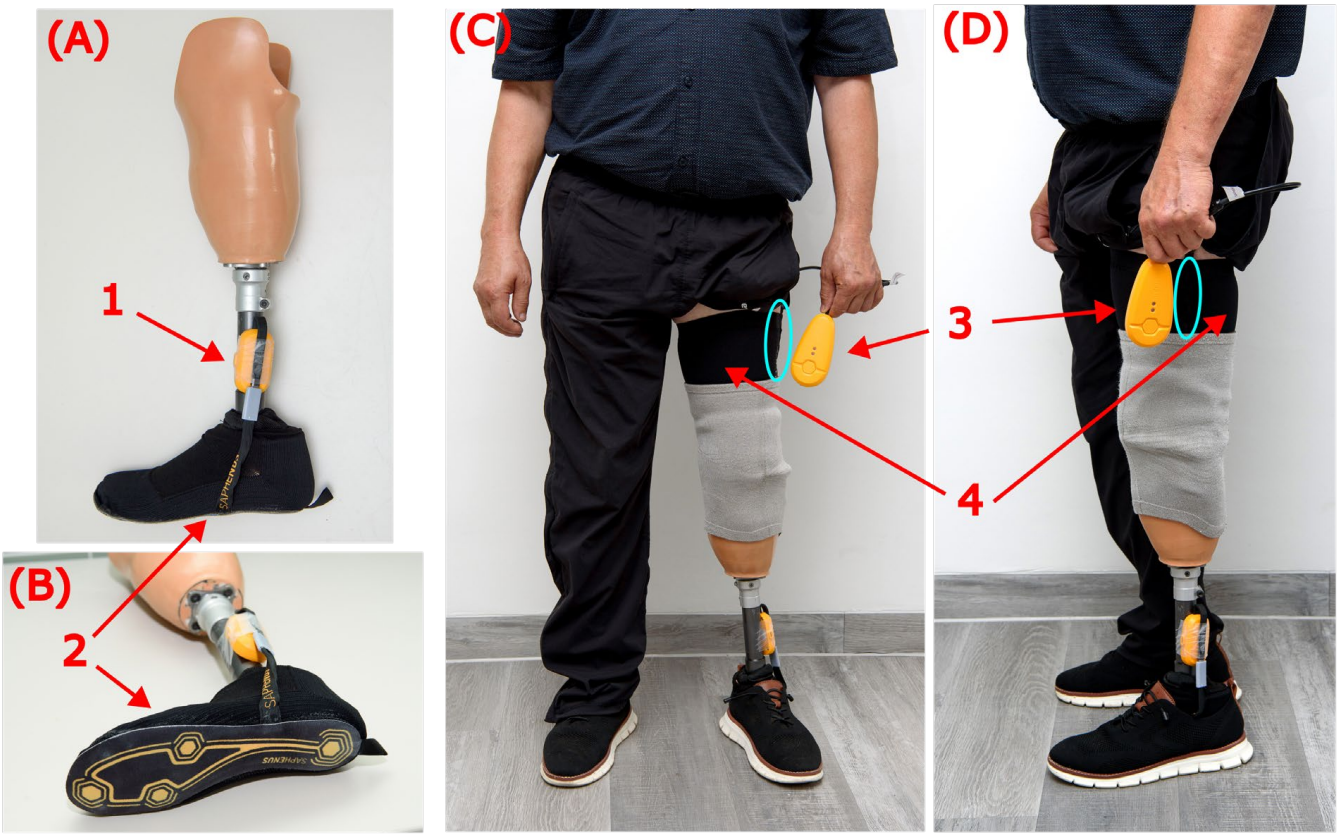

Figure 3. Below-knee amputee (BKA) (patient 4), who is fitted with the VTFS. (**A**) Lateral view of the fitted prosthesis: (1) transmitter unit, temporarily attached to the prosthetic tube. (**B**) Bottom view of the fitted prosthesis: (2) sensor sleeve worn over the prosthetic foot component. (**C**) Anterior view of the patient fitted with the VTFS: (3) Actuator unit; (4) elastic leg cuff with embedded vibrotactile actuators (marked in blue). (**D**) Lateral view of the patient.

Following the fitting, the subjects were equipped with the feedback system for at-home usage for a minimum duration of 30 days and a maximum until the next clinical routine appointment (see Figure 4). All the subjects were instructed to use the system every time they walked with the prosthesis. The actual time in days that the VTFS was tested was documented for each subject.

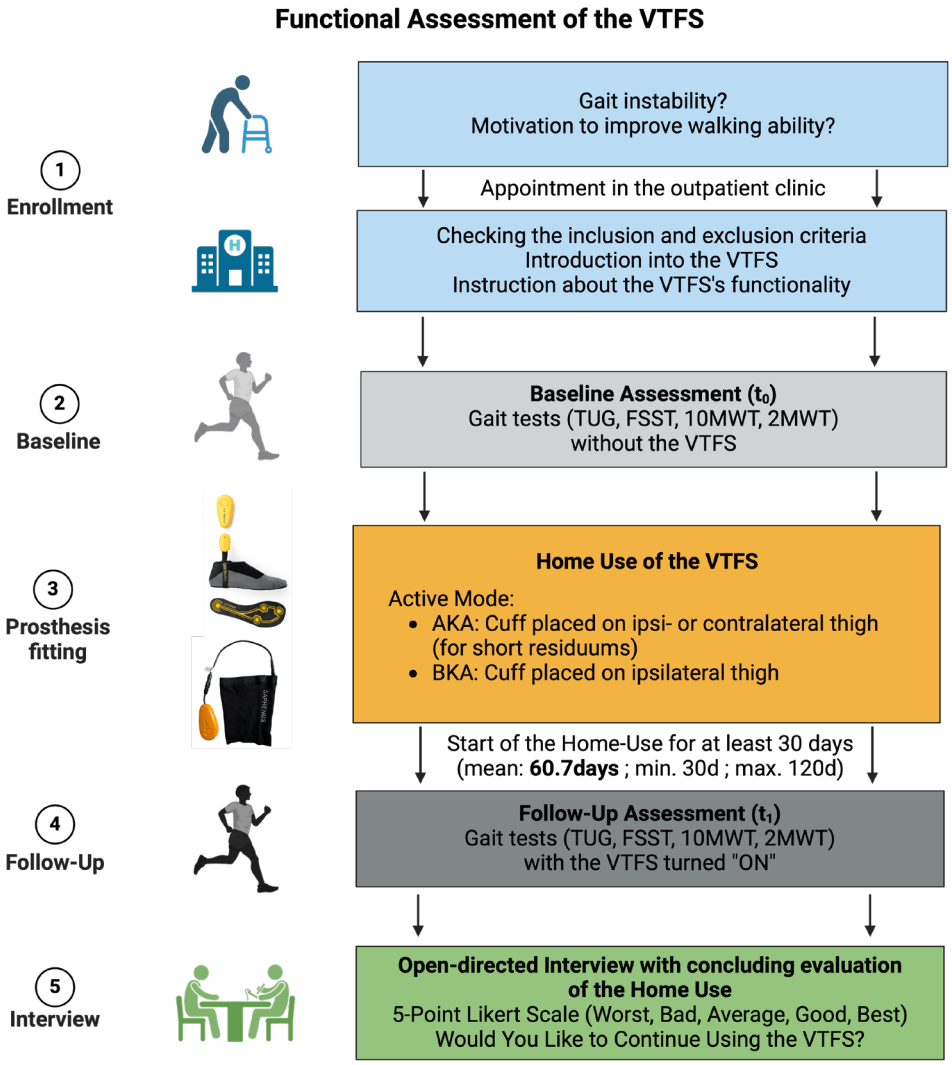

Figure 4. Flow chart of the study protocol. The assessment procedure for home testing of the vibrotactile feedback system (VTFS) involved the recruitment of subjects reporting gait instability who met the inclusion criteria. Participants were equipped with a VTFS and instructed to engage in home-based testing for a minimum of 30 days. Preceding the testing period, subjects underwent four gait tests without the system. Following the completion of the home testing period, the subjects were required to repeat the gait tests, this time with the VTFS activated. After the testing period, subjects rated their experience with the VTFS on a 5-point Likert scale and indicated whether they would like to continue using the system. (Images VTFS: Copyright Saphenus Medical Technology GmbH; Icons & flow chart created in BioRender. Ernst, J. (2024) (https://BioRender.com/a98g068, accessed on 9 October 2024).

2.5. Functional Gait Assessment

The included subjects performed four standardized gait tests prior (without the system) and after the testing period (with the system turned "On"). The performed gait tests included the Timed "Up and Go" Test (TUG) [33,34], the Four Square Step Test (FSST) [33], the 10 Meter Walk Test (10 MWT) [34] and the 2 Minute Walk Test (2 MWT) [35]. The TUG was used to evaluate the parameter risk of falling [36,37], the FSST to evaluate the parameter coordination [35], the 10 MWT to evaluate the parameter walking speed [36] and the 2 MWT to evaluate the parameter endurance [37]. Gait tests were performed in a 30 m corridor marked at 1 m intervals, with performance times recorded using a stopwatch. The TUG, FSST and 10 MWT were each performed three times, with mean values calculated afterward, while the 2 MWT was performed only once. For the 10 MWT, the walking

speed was calculated by dividing 10 m by the time required to perform the test. For the 2 MWT, the distance covered within 2 min was recorded using the 1 m intervals on the floor. Subjects were permitted to use walking aids (e.g., crutches, canes), but assistance from others was not allowed during the gait tests.

2.6. Further Assessed Parameters

In addition to the gait tests, the following demographic and amputation-related data were documented: age, sex, comorbidities, medication, time since amputation, cause of amputation, affected body side, amputation level, Medicare Functional Classification Level (K-Level) before the intervention, type of amputation procedure, e.g., standard (myodesis, myoplasty) or innovative (Osseointegration (OI), Agonist–Antagonist Myoneural Interface (AMI), Targeted Sensory Reinnervation (TSR), Targeted Muscle Reinnervation (TMR)) and individual usage time of the VTFS. After the testing of the VTFS, the subjects underwent an open-directed interview with a concluding evaluation of the home testing. They were asked to rate their experience on a 5-Point Likert Scale (Worst, Bad, Average, Good, Best), indicate whether they would like to continue using the VTFS and share any meaningful observations.

2.7. Statistical Analysis and Data Evaluation

To evaluate the impact of gait-synchronized vibrotactile stimulation on the walking ability of lower limb amputees, we calculated the median and the interquartile range (IQR) for the entire cohort as well as the mean performance of the individual subjects at baseline and follow-up for each walking test (see Appendix A, Tables A1 and A2). Furthermore, we determined the absolute and relative changes between the two measurements for both the entire cohort and individual subjects across all gait tests (see Appendix A, Tables A1 and A2). The statistical analysis of the data was conducted using Microsoft Excel (Version 16.91) and Matlab (MathWorks, Version R2024a). Due to the small sample size, no assumptions regarding the normal distribution of the sample could be made; hence, the Wilcoxon signed-rank test was utilized for further statistical analysis. The significance level was set at a p-value of <0.05.

The assessed performance data at baseline and follow-up were compared to each other. The results were evaluated regarding the presence of Minimal Detectable Changes (MDC) and Minimal Clinically Important Differences (MCID) for a unilaterally amputated cohort (see Table 1). Additionally, correlation analyses were conducted between the individual performance of the subjects ($\Delta t_1 - t_0$) and both the usage time of the VTFS at home and the time since amputation.

Table 1. Minimum Detectable Change (MDC) and Minimal Clinically Important Difference (MCID) values for the Timed Up and Go (TUG), Four Square Step Test (FSST), 10 Meter Walk Test (10 MWT), and 2 Minute Walk Test (2 MWT) for unilateral amputees. To assess the clinical significance of the changes in the evaluated gait parameters in this study, the results were compared to existing MCID values. In cases where no MCID value for the respective test had been reported in the literature, the Minimum Clinically Detectable (MCD) value was utilized (n.a. = not available).

Gait Test	MCID	MDC
Timed "Up and Go" Test	n.a.	3.6 s [38] 2.2 s [39]
Four Square Step Test	n.a.	2.0 s [39]
10 Meter Walk Test	0.21 m/s [40]	n.a.
2 Minute Walk Test	37.2 m [40]	n.a.

3. Results

3.1. Demographics

Of the eleven included subjects, ten (91%) were male and one (9%) female. The average age of the examined cohort was 55.82 (±12.50) years, and the mean time since amputation was 6.91 (±8.35) years. Five subjects (45.5%) were amputated at the level of the lower leg (below-knee amputation, (BKA)), two subjects (18.1%) had a knee disarticulation (KD) and four subjects (36.4%) were amputated at the thigh level (above-knee amputation, (AKA)). The left side was predominantly affected (63.6%), while the right side and bilateral amputations accounted for 18.2% each. Subject 10, who had undergone amputation on both sides, tested the feedback system bilaterally, while subject 11, also a bilateral amputee with a below-knee amputation (BKA) and above-knee amputation (AKA), exclusively tested the system on the left side (AKA). Trauma was the primary cause of amputation in the study population (45.5%), followed by vascular disorders (27.2%), accompanied by diabetes mellitus (13.6%). Other causes for amputation included tumor disease (9.1%), infection (9.1%), and chronic pain syndrome (9.1%). The average level of mobility (Medicare Functional Classification Level (K-Level)) before the intervention was 2.6 (±0.81). Four patients (36.4%) underwent standard lower limb amputation, two (18.2%) received an Agonist–Antagonist Myoneural Interface (AMI), two (18.2%) underwent Targeted Muscle Reinnervation (TMR) and two (18.2%) have an osseointegrated prosthesis (OI). One of the subjects (subject 5) had undergone a Targeted Sensory Reinnervation surgery (TSR) prior to the study, while the remaining 10 subjects had not undergone any TSR surgery [30] (see Table 2).

Table 2. Summary of subjects' demographic and amputation-related characteristics. BKA = below-knee amputation, KD = knee disarticulation, AKA = above-knee amputation, TSR = Targeted Sensory Reinnervation, TMR = Targeted Muscle Reinnervation, OI = Osseointegration, AMI = Agonist–Antagonist Myoneural Interface, K-Level = Medicare Functional Classification Level, VTFS = vibrotactile feedback system.

Subject (p#)	Sex	Age	Amputation Level	Affected Side	Cause of Amputation	Type of Procedure	K-Level	Time Since Amputation [Years]	VTFS Usage Time [Days]
1	Female	59	BKA	Right	Infection	Standard	2	9	36
2	Male	61	BKA	Left	Chronic pain syndrome and vascular disorder	AMI	2	2.25	120
3	Male	69	BKA	Right	Vascular disorder and diabetes	Standard	3	9	34
4	Male	63	BKA	Left	Trauma	TMR	2	1	86
5	Male	73	BKA	Left	Vascular disorder and diabetes	TSR	2	1.6	30
6	Male	28	KD	Left	Tumor	AMI	4	1.4	36
7	Male	62	KD	Left	Vascular disorder	Standard	3	4	71
8	Male	52	AKA	Left	Trauma	OI	3	2.5	120
9	Male	60	AKA	Left	Trauma	Standard	4	30	50
10	Male	41	AKA	Bilateral	Trauma	OI	2	14	64
11	Male	46	Right: BKA Left: AKA	Bilateral	Trauma	TMR	2	1.3	30

3.2. Results: Intervention

The included subjects (n = 11) walked with the vibrotactile feedback system at home for an average of 61.5 days (min. 30–max. 120 days) (see Table 2).

3.3. Results: Functional Gait Assessments

During the baseline assessment, subject 10 was unable to perform the 10 MWT and the 2 MWT due to pain. Therefore, he was excluded from the cohort analysis for the 10 MWT and the 2 MWT (n = 10).

In Figure 5, the median and interquartile range for the entire cohort in the TUG, FSST, 10 MWT and 2 MWT at both baseline and follow-up gait assessments are depicted. The

difference in medians indicates that subjects required less time to complete the TUG and FSST, walked slower during the 10 MWT, and covered longer distances in the 2 MWT following the VTFS intervention. However, the results of the Wilcoxon signed-rank test showed that only the difference in TUG performance was statistically significant ($p = 0.042$ *). This suggests a notable improvement in the cohort's TUG results following the intervention. No statistically significant changes were observed in the other three gait tests from baseline to follow-up (FSST: $p = 0.054$; 10 MWT: $p = 0.106$; 2 MWT: $p = 0.432$).

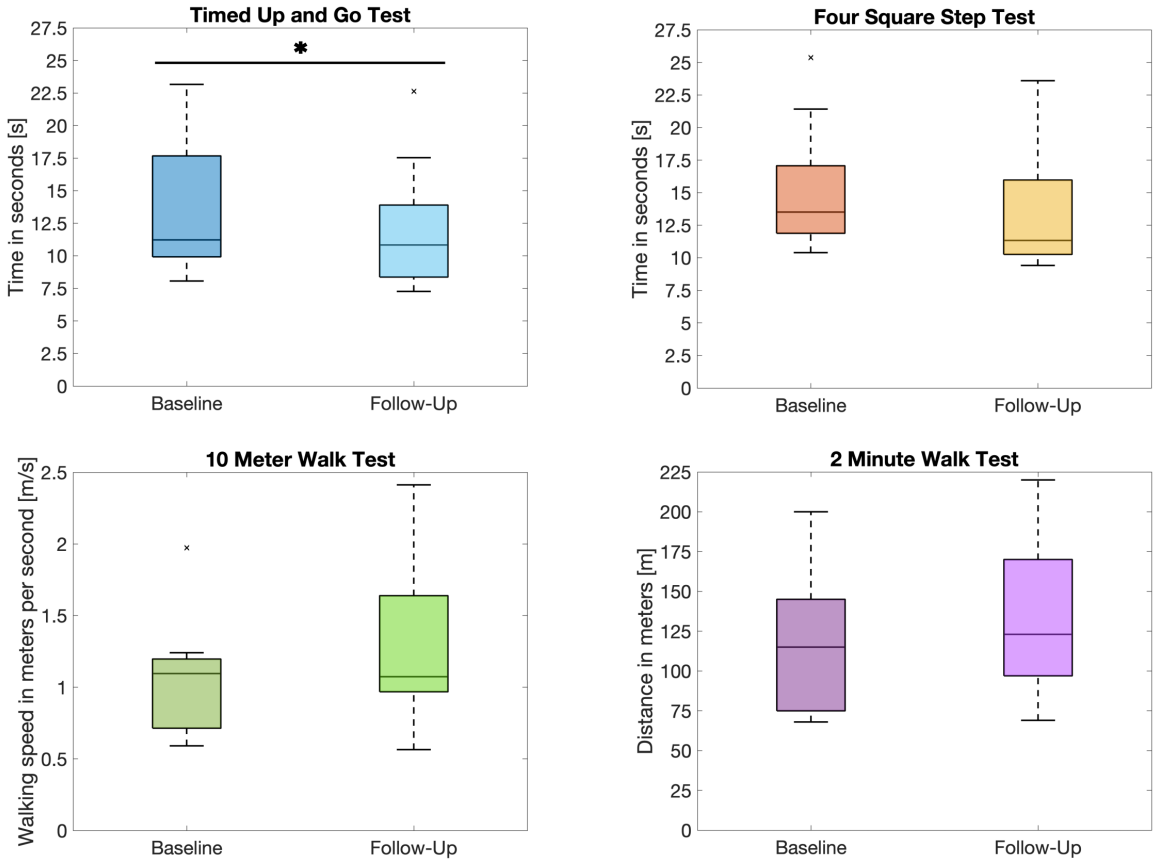

Figure 5. The boxplots illustrate the comparison of the cohort's performance at baseline and after the intervention during the follow-up for the Timed Up and Go (TUG) ($n = 11$), Four-Square Step Test (FSST) ($n = 11$), 10 Meter Walk Test (10 MWT) ($n = 10$), and 2 Minute Walk Test (2 MWT) ($n = 10$) using boxplots. The results of the Wilcoxon signed-rank test indicate that only the TUG demonstrated a significant change, implying an improvement in the cohort's performance following the intervention ($p = 0.042$ *). The comparison with the MDC and MCID reference values shows that the cohort exhibits an intervention-related change only in the FSST. Outliers are marked with 'x' and statistical significance is indicated by '*'.

3.3.1. Timed "Up and Go" Test—Risk of Falling

In the TUG, eight subjects (73%) showed an absolute decrease in the required time when walking at the follow-up assessment with vibrotactile stimulation, while three subjects (27%; p# 2, 4 and 9) required more time (see Figure 6). Out of those eight subjects, three subjects (27%; p# 1, 7 and 11) exhibited a relative decrease of up to 10%, two subjects (18%; p# 3 and 6) showed a relative decrease between 10% and 20% and in three subjects (27%; p# 5, 8 and 10), the required time decreased by over 20%. The maximum relative decrease was −32% (p# 5), and the maximum relative increase was 7.1% (p# 4).

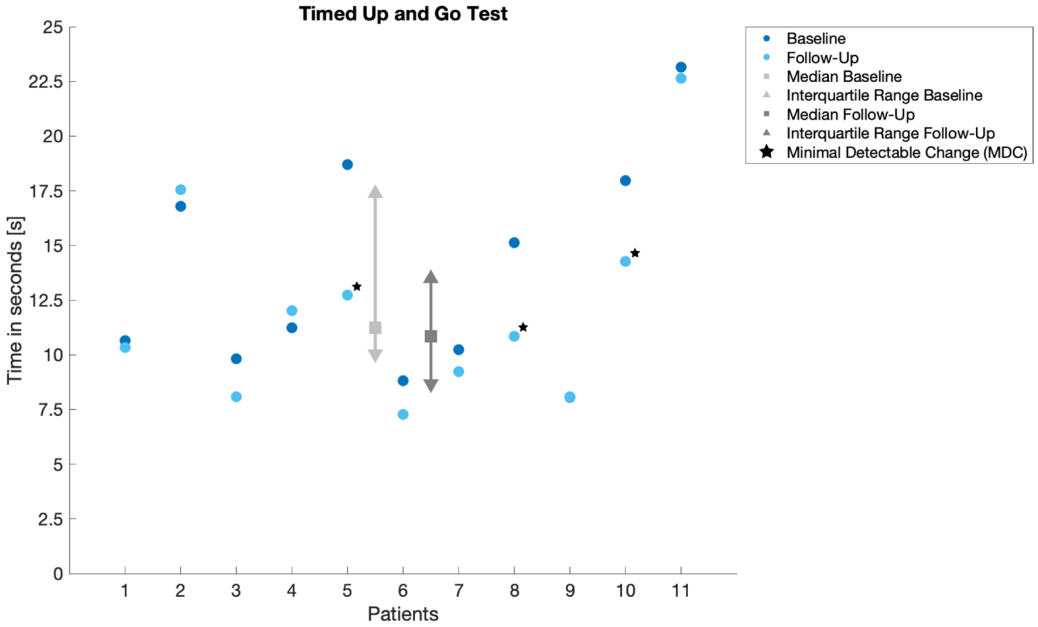

Figure 6. Scatter plot visualizing the mean performance of individual subjects, along with the median and IQR of the cohort's overall performance in the Timed "Up and Go" Test (TUG) at baseline (light gray) and follow-up (dark gray). Subjects whose performance changes exceeded the minimum detectable change (MDC) after the intervention are highlighted with a star (★).

The correlation analyses showed a weak, non-significant negative correlation between individual performance ($\Delta\ t_1 - t_0$) and both the VTFS usage time (r = 0.126, p = 0.713) and the time since amputation (r = 0.142, p = 0.678).

A comparison of the medians for the entire cohort (n = 11) before and after the intervention indicates a significant change in performance in the TUG (see Figure 5, p = 0.042 *; medians (IQR): 11.23 s (7.35 s) vs. 10.84 s (4.84 s)). The reduction in the median time required to perform the test for the entire cohort from the initial to the follow-up measurement was 0.39 s.

3.3.2. Four Square Step Test—Coordination

Except for two subjects (18%, p# 2 and 4), all subjects (82%) showed an absolute decrease in the required time to perform the FSST after the intervention (see Figure 7). Three subjects (27%; p# 5, 6 and 7) could decrease the time needed to perform the test by up to 10%, five subjects (45%; p# 1, 3, 8, 9 and 10) by up to 10–20%, and one subject (9%; p# 11) by 27.3%. Subject 4 showed the maximum relative increase (19.2%) after the intervention, and subject 2 showed a relative increase of 10.6%.

For the FSST, the correlation analyses revealed a moderate, non-significant negative correlation between individual performance and VTFS usage time (r = 0.518, p = 0.102) and a very weak, non-significant positive correlation between performance and time since amputation (r = −0.154, p = 0.651).

In contrast to the TUG, no significant difference was observed in the medians of the entire cohort (n = 11) before and after the intervention in the FSST (see Figure 5, p = 0.0537; medians (IQR): 13.51 s (4.54 s) vs. 11.33 s (5.55 s)). The difference in medians between the two measurements for the entire cohort showed an absolute decrease in the test performance time of 2.18 s.

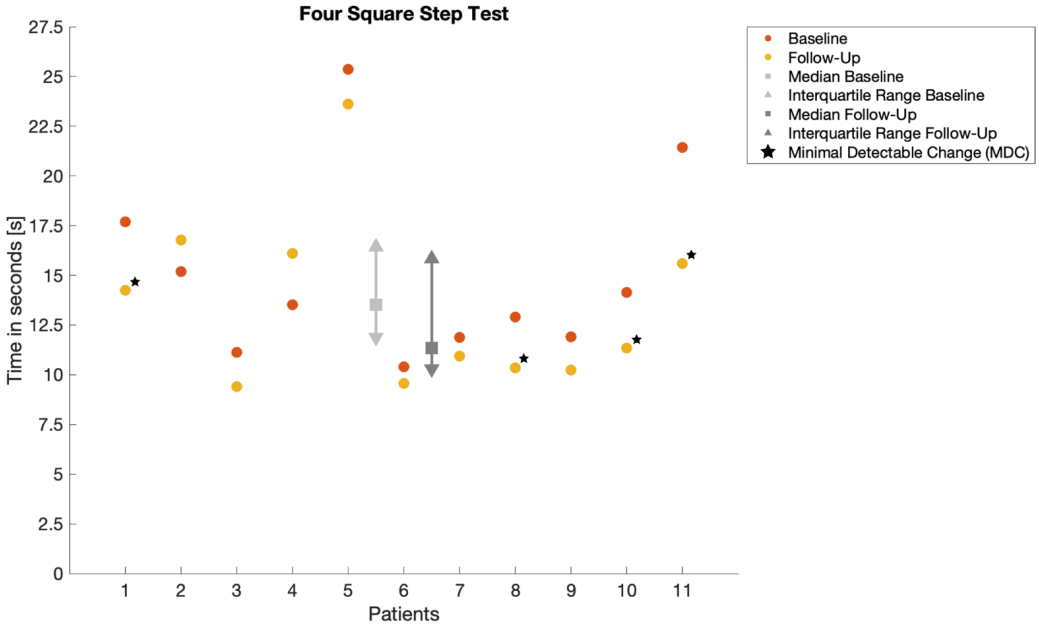

Figure 7. Scatter plot visualizing the mean performance of each subject, along with the median and IQR of the cohort's overall performance in the Four Square Step Test (FSST) at baseline (light gray) and follow-up (dark gray). Subjects with performance changes surpassing the MDC after the intervention are highlighted with a star (★).

3.3.3. 10 Meter Walk Test—Walking Speed

Consistent with the findings of the FSST, all subjects except for two (18%; p# 2 and 4) demonstrated an absolute improvement in walking speed over a 10 m distance following the intervention period and while utilizing the vibrotactile feedback system in the 10 MWT at Follow-Up (see Figure 8). However, the median walking speed decreased by 0.09 s from the initial to the follow-up measurement. Three subjects (27%; p# 8, 9 and 11) increased their walking speed by up to 10%, one (9%; p# 1) by over 10% and the remaining four subjects (36%; p# 3, 5, 6 and 7) walked more than 30% faster in the follow-up measurement. The maximum relative increase in walking speed was 100.8% (p# 7). Subjects 2 and 4 slowed down by 21.2% and 12.5%, respectively.

For the 10 MWT, there was a very weak, non-significant negative correlation between individual performance and VTFS usage time ($r = -0.173$, $p = 0.61$) as well as a very weak, non-significant positive correlation to the time since amputation ($r = 0.099$, $p = 0.77$).

In line with the findings of the FSST, our study likewise observed a lack of significant difference in the medians of the cohort ($n = 10$) between the two measurements in the 10 MWT, with a difference of −0.02 m/s (see Figure 5, $p = 0.106$; medians (IQR): 1.10 m/s (0.44 m/s) vs. 1.07 m/s (0.65 m/s)).

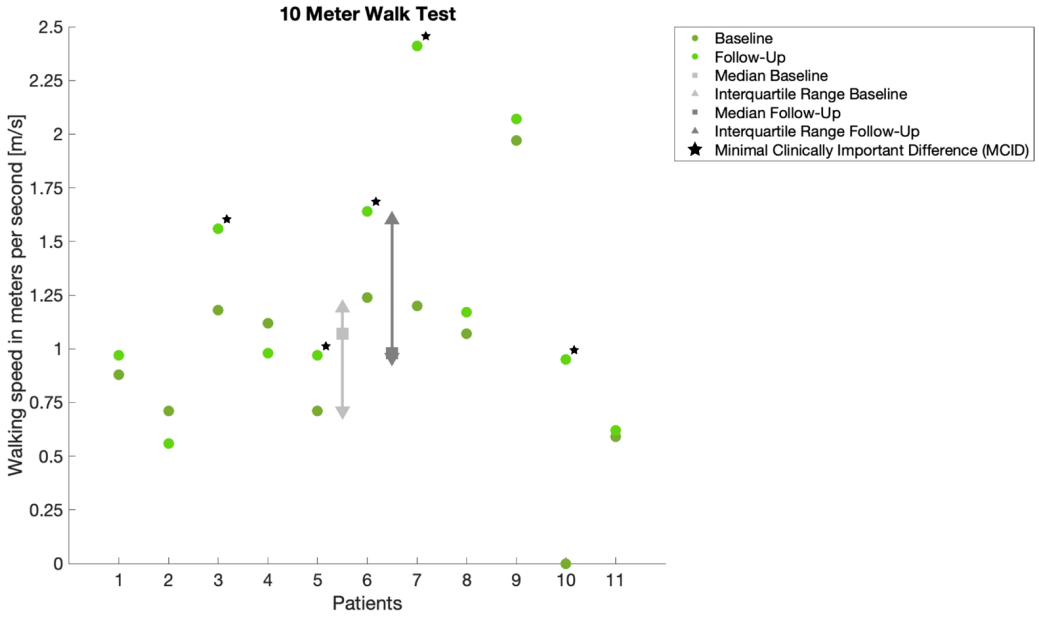

Figure 8. Scatter plot visualizing the mean performance of each subject, along with the median and IQR of the cohort's overall performance in the 10 Meter Walk Test (10 MWT) at baseline (light gray) and follow-up (dark gray). Subjects with performance changes surpassing the MCID after the intervention are highlighted with a star (★).

3.3.4. 2 Minute Walk Test—Endurance

In the 2 MWT, seven subjects (64%) walked longer distances within two minutes at the follow-up assessment, while four subjects (36%; p# 1, 2, 4 and 6) showed an absolute decrease in the distance walked (see Figure 9). Two subjects (18%; p# 9 and 11) increased their walking distance by up to 10%, and four subjects (36%; p# 3, 5, 7 and 8) by over 20%. Subject 5 achieved the highest absolute increase in walking distance at 49.3%. The maximum relative decrease in walking distance was −25.1% (p# 6).

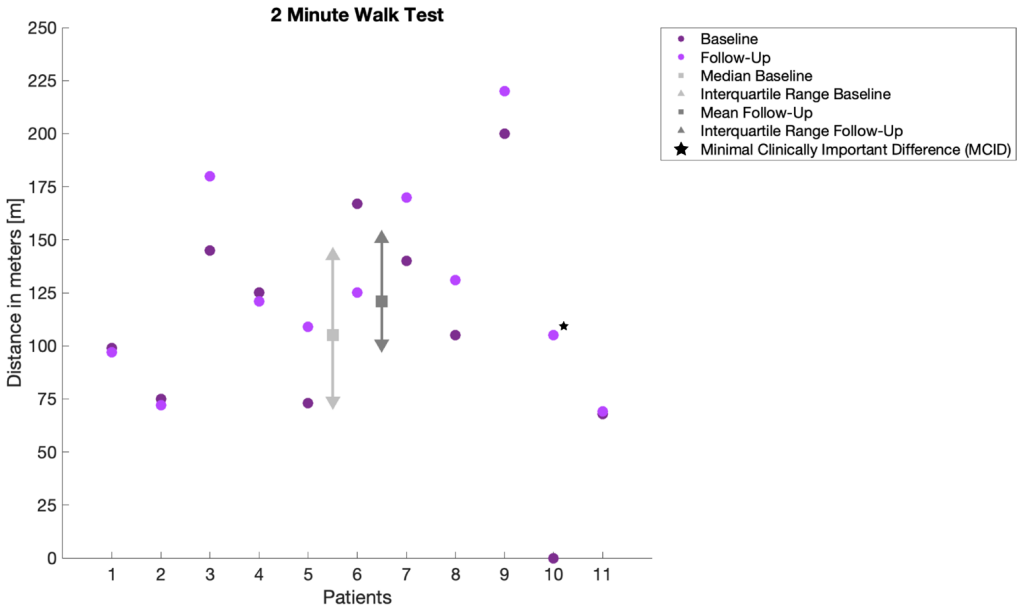

Figure 9. Scatter plot visualizing the mean performance of each subject, along with the median and IQR of the cohort's overall performance in the 2 Minute Walk Test (2 MWT) at baseline (light gray) and follow-up (dark gray). Subjects with performance changes surpassing the MCID after the intervention are highlighted with a star (★).

The correlation analyses revealed a very weak, non-significant positive correlation between individual performance and both the VTFS usage time (r = 0.044, p = 0.899) and the time since amputation (r = 0.354, p = 0.285).

No significant difference was observed in the medians for the 2 MWT after the intervention (n = 10) and when walking with the vibrotactile feedback system (see Figure 5, p = 0.432; medians (IQR): 115 m (62.8 m) vs. 123 m (60.3 m)). The absolute increase in median walking distance was 8 m.

3.4. Open-Directed Interview

Table 3 shows the results of the open-directed interview, which the subjects underwent after finishing the testing period. The subjects had to rate their experience with the VTFS on a 5-Point Likert Scale and should give feedback on the home-use. Furthermore, they had to state if they would prefer to continue using the VTFS.

Table 3. Results of the open-directed interview with concluding evaluation of the home-use. Subjects had to rate their experience with the vibrotactile feedback system (VTFS) on a 5-Point Likert Scale (Worst, Bad, Average, Good, Best). Additionally, they had to indicate whether they would like to continue using the VTFS.

Subject (p#)	Rating 5-Point Likert Scale	Feedback
1	Good	Would like to continue using the system. Coverage by health insurance has been requested.
2	Average	Little effect in the subject's opinion. Currently not walking at all because of contralateral knee pain. Knee arthroplasty scheduled. Wants to test again afterward.
3	Good	Complete resolution of Phantom Limb Pain and better gait stability. Subject suspects a carryover effect and does not want to continue.
4	Average	Little effect in the subject's opinion; handling the cables was inconvenient. Does not want to continue.
5	Best	Complete resolution of Phantom Limb Pain and better gait stability. Would like to continue using the system. Coverage by health insurance requested.
6	Good	Good but the effect was not groundbreaking. Does not want to continue.
7	Best	Complete resolution of Phantom Limb Pain. Would like to continue using the system. Coverage by health insurance requested.
8	Average	Liked the system, but handling the cables was inconvenient. Does not want to continue.
9	Best	Complete resolution of Phantom Limb Pain. Would like to continue using the system. Coverage by health insurance requested.
10	Good	Liked the system, but as subject is wearing an osseointegrated prosthesis, subject does not want any external components on the residuum.
11	Average	Little effect in the subject's opinion; handling the cables was inconvenient. Does not want to continue.

Four subjects (36%; p# 2, 4, 8 and 11) reported an average experience with the system, four (36%; p# 1, 3, 6 and 10) rated their experience as good, and three (27%; p# 5, 7 and 9) rated it as "best". Five subjects (45%; p# 1, 2, 5, 7 and 9) wanted to continue using the VTFS, and cost coverage by the health insurance has been requested.

4. Discussion

The goal of this study was to determine the impact of a non-invasive VTFS on gait characteristics such as risk of falling, coordination, walking speed and endurance of lower limb amputees. The results indicate a significantly improved performance of the overall

cohort for the TUG (p = 0.042 *), with 73% of the subjects reducing the required time to perform the test successfully.

In the subsequent analyses of the three additional gait assessments, no statistically significant differences were observed. However, the results of the FSST showed a p-value close to 0.05, indicating a potential trend toward meaningful change. Notably, 82% of the participants demonstrated a reduction in the time required to complete the FSST, and similarly, 82% exhibited an increase in walking speed in the 10 MWT. Furthermore, 64% of the subjects in the 2 MWT were able to cover a greater distance within two minutes following the intervention with the VTFS, with a smaller interquartile range (IQR) suggesting more consistent data (see Figure 5).

Another potential contributing factor could be the relatively brief intervention period, which contrasts with the average time since amputation (6.91 $\pm$ 8.35 years) observed within this cohort.

The TUG and FSST reference values indicating an elevated risk of falling for unilateral lower limb amputees are 19 s for TUG, and 24 s for FSST [33]. Except for two subjects (p# 11 for TUG, p# 5 for FSST), the entire cohort exhibited no increased fall risk based on the reference values even prior to the intervention (refer to Figures 6 and 7). Consequently, our findings suggest a generally low fall risk for the study cohort despite significant limb amputations, indicating that the VTFS does not contribute to an increased risk of falling for amputees.

To assess the effects of the VTFS intervention on changes in the TUG and FSST, the minimal detectable change (MDC) values from Table 1 [38,39] were utilized for reference. In the TUG, the cohort's median improvement in performance time was 0.39 s, falling below the minimal detectable change (MDC) reference value for the TUG [38,39]. Although a statistically significant change in the TUG was observed, determining the exclusive attribution of this change to the intervention remains uncertain.

Regarding the FSST, the cohort exhibited a median improvement of 2.18 s, surpassing the established MDC reference value, suggesting intervention-based improvement for the entire cohort. Additionally, three subjects in the TUG (27%; subjects 5, 8, and 10) and four subjects in the FSST (36%; p# 1, 8, 10, and 11) demonstrated improvements that exceeded the minimal detectable change (MDC) values, indicating potential intervention-based benefits for these individuals.

It is important to note the lack of established minimal clinically important difference (MCID) values for the TUG and FSST in the literature, which raises uncertainty about the final clinical significance of these changes.

The 10 MWT and the 2 MWT are commonly used functional assessments for evaluating an individual's gait speed and walking endurance, which are indicative of their physical functionality and ability to use prosthetics [41,42]. Gaunaurd et al. previously established normative values for the 10 MWT and 2 MWT in unilaterally amputated subjects, with an average walking speed of 72.1 $\pm$ 18.8 m/min (equivalent to 1.20 $\pm$ 0.31 m/s) and an average walking distance of 143.8 $\pm$ 37.5 m [35]. In our study, the cohort's median walking speed remained within these ranges at both the initial and follow-up measurements, indicating normative values for amputated subjects (see Figure 8). For the 2 MWT, the cohort's median walking distance was initially below the normative value but increased to fall within the normative range after the intervention (see Figure 9). On an individual level, two subjects (18%; p# 2 and 11) exhibited walking speeds below the norm, while four subjects (36%; p# 3, 6, 7 and 9) even exceeded the norm after the intervention with the VTFS. In terms of walking distance, six subjects (55%; p# 1, 2, 5, 8, 10 and 11) initially fell below the established standard (see Figure 9). However, the intervention improved endurance to within the normative range for three of these subjects (27%; p# 5, 8 and 10). These absolute improvements suggest that the intervention with the VTFS enhanced the parameters of walking speed, distance, and gait stability in the amputated cohort.

To evaluate the clinical significance of the observed changes in the 10 MWT and the 2 MWT, we referenced the minimal clinically important difference (MCID) values as outlined in Table 1 [40]. Surprisingly, the cohort's median walking speed slightly decreased following

the intervention (−0.02 m/s). However, it should be noted that five subjects (45%; p# 3, 5, 6, 7 and 10) experienced clinically relevant improvements in walking speed as a result of the VTFS intervention, as illustrated in Figure 8. Conversely, no clinically significant improvement was observed in walking distance for the overall cohort, with only one subject (9%; p# 10) achieving a clinically relevant increase in this parameter, as depicted in Figure 9.

Studies could not show a clear correlation between the 10 MWT and 2 MWT [40,43]. Our findings may suggest that supplementary feedback had a more pronounced impact on fast movements, such as walking speed, coordination and balance, as opposed to endurance, which is predominantly an individual achievement of long-term rehabilitation.

Two subjects (p# 2 and 4) showed an absolute decrease in performance across all four gait tests. Subject 2 suffered from a Complex Regional Pain Syndrome (CRPS) before his below-knee amputation, and unfortunately, although the CRPS reduced, it persisted after the amputation. During the intervention time the contralateral knee arthrosis pain of subject 2 increased, which most probably reduced the overall walking ability. Subject 4 developed a painful neuroma at the residual limb and underwent a revision surgery [44–46]. The ongoing rehabilitation process after surgery may have contributed to the decreased performance in the assessed gait parameters at follow-up.

Subject 10 was unable to complete the baseline test due to recent skin-penetration site revision surgery. The follow-up measurement took place 3.5 months after the surgery, using a cane. Overall, the results do not allow differentiation of the underlying factor for the observed improvement.

After an average testing period of 61.5 days, the VTFS significantly improved gait stability (TUG). Overall, 36% showed an intervention-related improvement in coordination (FSST), 45% a clinically relevant improvement in gait speed (10 MWT) and 9% in endurance (2 MWT). In total, 63% rated their experience with the VTFS as "good" or better and 45% wanted to continue using the VTFS. In addition, 36% reported only a minor effect and found the handling of the system's wires problematic. However, this issue will be resolved in the final implementation of the system, where a vibratory actuator pad and the wires will be integrated into the socket of the prosthesis.

It is noteworthy to emphasize that subject 5, the only subject who underwent TSR surgery prior to the intervention, demonstrated some of the most significant improvements following the implementation of the VTFS. This subject exhibited unequivocal improvements across all four gait tests, including an intervention-induced enhancement in the TUG, as well as a clinically relevant increase in walking speed during the 10 MWT. Furthermore, he rated his experience as "best", reported a complete resolution of phantom limb pain and wanted to continue using the system.

This finding suggests that sensory reinnervation and restoration of somatotopy may unlock the full potential of the VTFS.

Limitations

This study recognizes several significant limitations that should be considered when interpreting the results. The lack of statistical significance in our cohort may not solely stem from the ineffectiveness of the applied vibrotactile non-somatotopical feedback but may also be attributed to limitations in the study design, including the observation period, and sample size. The small sample size of eleven subjects restricts the generalizability of the results and hinders comparisons based on varying biomechanical properties, such as residual limb length, amputation level, level of mobility (K-Level), or unilateral versus bilateral amputations. While reference values from previous studies can be useful for categorizing subjects' performance in gait tests, their applicability for evaluating our study's data is restricted. The reference values were derived from unilateral amputee cohorts and did not account for different amputation levels, despite the substantial impact that amputation level can have on walking ability and gait stability [4,47–52].

Additionally, the observation period, spanning from 30 to 120 days, may not have captured the long-term effects and full impact of the device on the gait of lower limb

amputees, particularly considering the average time since amputation of 6.91 (± 8.35) years. Although no correlation was found between the individual performance of the subjects and either the VTFS usage time or the time since amputation, a longer observation period or larger sample size may reveal potential long-term effects or correlations.

Testing the system on a larger sample size, including both TSR and non-TSR patients, could better evaluate the differences between these groups using the VTFS. Furthermore, this study primarily focused on functional assessment and effects of the sensory feedback device on gait without addressing other important aspects of amputees' lives, such as amputation-related pain and prosthesis embodiment, which are known to significantly influence subjects' quality of life and well-being.

5. Conclusions

In this study, we examined the effects of a non-invasive, gait-synchronized, vibrotactile feedback system on the walking ability of eleven lower limb amputees. We assessed various aspects of walking, including risk of falling (TUG), coordination (FSST), walking speed (10 MWT), and endurance (2 MWT). Overall, we found a reduced risk of falling when walking with the VTFS (TUG, $p = 0.0420$ *), with a trend of significant change in coordination (FSST).

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Institutional Review Board Statement: The study was conducted in accordance with the WMA Declaration of Helsinki and approved by the Ethics Committee of Hannover Medical School (10940_BO_K_2023) on 13 June 2023.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Appendix A

Table A1. Results of the functional gait assessment (TUG, FSST) for all subjects (p#, $n = 11$). Changes between initial (t0) and follow-up (t1) measurement are shown in absolute and relative terms (%). A decrease in the required time to perform the test tests is indicated in green. Respectively, an increase is displayed in red. TSR = Targeted Sensory Reinnervation, TMR = Targeted Muscle Reinnervation, OI = Osseointegration, AMI = Agonist–Antagonist Myoneural Interface.

Subject (p#)	Mean Value TUG (t0) [t in s]	Mean Value TUG (t1) [t in s]	ΔTUG [t in s]	Mean Value FSST (t0) [t in s]	Mean Value FSST (t1) [t in s]	ΔFSST [t in s]	Type of Procedure
1	10.65	10.34	−0.31 (−2.9%)	17.69	14.26	−3.43 (−19.4%)	Standard
2	16.80	17.54	0.74 (4.4%)	15.18	16.79	1.61 (10.6%)	AMI

Table A1. *Cont.*

Subject (p#)	Mean Value TUG (t0) [t in s]	Mean Value TUG (t1) [t in s]	ΔTUG [t in s]	Mean Value FSST (t0) [t in s]	Mean Value FSST (t1) [t in s]	ΔFSST [t in s]	Type of Procedure
3	9.83	8.08	−1.75 (−17.8%)	11.12	9.41	−1.71 (−15.4%)	Standard
4	11.23	12.03	0.8 (7.1%)	13.51	16.10	2.59 (19.2%)	TMR
5	18.71	12.73	−5.98 (−32%)	25.36	23.60	−1.76 (−6.9%)	TSR
6	8.83	7.27	−1.56 (−17.7%)	10.40	9.56	−0.84 (−8.1%)	AMI
7	10.23	9.23	−1.00 (−9.8%)	11.88	10.93	−0.95 (−8.0%)	Standard
8	15.14	10.84	−4.30 (−28.4%)	12.91	10.35	−2.56 (−19.8%)	OI
9	8.07	8.09	0.02 (0.2%)	11.90	10.24	−1.66 (−13.9%)	Standard
10	17.96	14.28	−3.68 (−20.5%)	14.14	11.33	−2.81 (−19.9%)	OI
11	23.16	22.64	−0.52 (−2.2%)	21.42	15.58	−5.84 (−27.3%)	TMR
Median	11.23	10.84	−0.39	13.51	11.33	−2.18	

Table A2. Results of the functional gait assessment (10 MWT, 2 MWT) for all subjects (p#). Changes between initial (t0) and follow-up (t1) measurement are shown in absolute and relative terms (%). An increase in walking speed in the 10 MWT as well as an increase in walking distance in the 2 MWT are indicated in green. Respectively, a decrease is displayed in red. As subject 10 was not able to perform the 10 MWT and 2 MWT at the baseline measurement due to pain, the relative change could not be calculated and the subject has been excluded from the cohort analysis for the 10 MWT and 2 MWT ($n = 10$). TSR = Targeted Sensory Reinnervation, TMR = Targeted Muscle Reinnervation, OI = Osseointegration, AMI = Agonist–Antagonist Myoneural Interface.

Subject (p#)	Mean Value 10 MWT (t0) [v in m/s]	Mean Value 10 MWT (t1) [v in m/s]	Δ10 MWT [v in m/s]	Mean Value 2 MWT (t0) [d in m]	Mean Value 2 MWT (t1) [d in m]	Δ2 MWT [d in m]	Type of Procedure
1	0.88	0.97	0.09 (10.2%)	99	97	−2 (−2.0%)	Standard
2	0.71	0.56	−0.15 (−21.2%)	75	72	−3 (−4%)	AMI
3	1.18	1.56	0.38 (32.2%)	145	180	35 (24.1%)	Standard
4	1.12	0.98	−0.14 (−12.5%)	125	121	−4 (−3.2%)	TMR
5	0.71	0.97	0.26 (36.6%)	73	109	36 (49.3%)	TSR
6	1.24	1.64	0.4 (32.3%)	167	125	−42 (−25.1%)	AMI
7	1.20	2.41	1.21 (100.8%)	140	170	30 (21.4%)	Standard
8	1.07	1.17	0.1 (9.3%)	105	131	26 (24.8%)	OI
9	1.97	2.07	0.1 (5.1%)	200	220	20 (10%)	Standard
10	0	0.95	0.95 (n.a.)	0	105	105 (n.a.)	OI
11	0.59	0.62	0.03 (5.1%)	68	69	1 (1.5%)	TMR
Median	1.07	0.98	−0.02	105	121	8	

References

1. Miller, W.C.; Speechley, M.; Deathe, B. The Prevalence and Risk Factors of Falling and Fear of Falling among Lower Extremity Amputees. *Arch. Phys. Med. Rehabil.* **2001**, *82*, 1031–1037. [CrossRef]
2. Fuchs, K.; Krauskopf, T.; Lauck, T.B.; Klein, L.; Mueller, M.; Herget, G.W.; Von Tscharner, V.; Stutzig, N.; Stieglitz, T.; Pasluosta, C. Influence of Augmented Visual Feedback on Balance Control in Unilateral Transfemoral Amputees. *Front. Neurosci.* **2021**, *15*, 727527. [CrossRef] [PubMed]
3. Nolan, L.; Wit, A.; Dudziñski, K.; Lees, A.; Lake, M.; Wychowañski, M. Adjustments in Gait Symmetry with Walking Speed in Trans-Femoral and Trans-Tibial Amputees. *Gait Posture* **2003**, *17*, 142–151. [CrossRef] [PubMed]
4. Waters, R.L.; Perry, J.; Antonelli, D.; Hislop, H. Energy Cost of Walking of Amputees: The Influence of Level of Amputation. *J. Bone Jt. Surg. Am.* **1976**, *58*, 42–46. [CrossRef]
5. Makin, T.R.; De Vignemont, F.; Faisal, A.A. Neurocognitive Barriers to the Embodiment of Technology. *Nat. Biomed. Eng.* **2017**, *1*, 14. [CrossRef]
6. Williamson, G.M.; Schulz, R.; Bridges, M.W.; Behan, A.M. Social and Psychological Factors in Adjustment to Limb Amputation. *J. Social Behav. Personal.* **1994**, *9*, 249–268.
7. Petrini, F.M.; Valle, G.; Strauss, I.; Granata, G.; Di Iorio, R.; D'Anna, E.; Čvančara, P.; Mueller, M.; Carpaneto, J.; Clemente, F.; et al. Six-Month Assessment of a Hand Prosthesis with Intraneural Tactile Feedback. *Ann. Neurol.* **2019**, *85*, 137–154. [CrossRef] [PubMed]

8. Blanke, O. Multisensory Brain Mechanisms of Bodily Self-Consciousness. *Nat. Rev. Neurosci.* **2012**, *13*, 556–571. [CrossRef] [PubMed]
9. Heller, B.W.; Datta, D.; Howitt, J. A Pilot Study Comparing the Cognitive Demand of Walking for Transfemoral Amputees Using the Intelligent Prosthesis with That Using Conventionally Damped Knees. *Clin. Rehabil.* **2000**, *14*, 518–522. [CrossRef]
10. Biddiss, E.; Beaton, D.; Chau, T. Consumer Design Priorities for Upper Limb Prosthetics. *Disabil Rehabil Assist. Technol.* **2009**, *2*, 346–357. [CrossRef]
11. Petrini, F.M.; Bumbasirevic, M.; Valle, G.; Ilic, V.; Mijović, P.; Čvančara, P.; Barberi, F.; Katic, N.; Bortolotti, D.; Andreu, D.; et al. Sensory Feedback Restoration in Leg Amputees Improves Walking Speed, Metabolic Cost and Phantom Pain. *Nat. Med.* **2019**, *25*, 1356–1363. [CrossRef] [PubMed]
12. Flor, H.; Nikolajsen, L.; Jensen, T.S. Phantom Limb Pain: A Case of Maladaptive CNS Plasticity? *Nat. Rev. Neurosci.* **2006**, *7*, 873–881. [CrossRef] [PubMed]
13. Dietrich, C.; Nehrdich, S.; Seifert, S.; Blume, K.R.; Miltner, W.H.R.; Hofmann, G.O.; Weiss, T. Leg Prosthesis with Somatosensory Feedback Reduces Phantom Limb Pain and Increases Functionality. *Front. Neurol.* **2018**, *9*, 336027. [CrossRef] [PubMed]
14. Rusaw, D.; Hagberg, K.; Nolan, L.; Ramstrand, N. Can Vibratory Feedback Be Used to Improve Postural Stability in Persons with Transtibial Limb Loss? *J. Rehabil. Res. Amp Dev.* **2012**, *49*, 1239–1254. [CrossRef]
15. Sensinger, J.W.; Dosen, S. A Review of Sensory Feedback in Upper-Limb Prostheses from the Perspective of Human Motor Control. *Front. Neurosci.* **2020**, *14*, 345. [CrossRef]
16. Cordella, F.; Ciancio, A.L.; Sacchetti, R.; Davalli, A.; Cutti, A.G.; Guglielmelli, E.; Zollo, L. Literature Review on Needs of Upper Limb Prosthesis Users. *Front. Neurosci.* **2016**, *10*, 175438. [CrossRef] [PubMed]
17. Raspopovic, S.; Valle, G.; Petrini, F.M. Sensory Feedback for Limb Prostheses in Amputees. *Nat. Mater.* **2021**, *20*, 925–939. [CrossRef]
18. Manz, S.; Valette, R.; Damonte, F.; Avanci Gaudio, L.; Gonzalez-Vargas, J.; Sartori, M.; Dosen, S.; Rietman, J. A Review of User Needs to Drive the Development of Lower Limb Prostheses. *J. Neuroeng. Rehabil.* **2022**, *19*, 119. [CrossRef]
19. Marasco, P.D.; Kim, K.; Colgate, J.E.; Peshkin, M.A.; Kuiken, T.A. Robotic Touch Shifts Perception of Embodiment to a Prosthesis in Targeted Reinnervation Amputees. *Brain* **2011**, *134*, 747–758. [CrossRef]
20. Antfolk, C.; D'Alonzo, M.; Controzzi, M.; Lundborg, G.; Rosen, B.; Sebelius, F.; Cipriani, C. Artificial Redirection of Sensation from Prosthetic Fingers to the Phantom Hand Map on Transradial Amputees: Vibrotactile versus Mechanotactile Sensory Feedback. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2013**, *21*, 112–120. [CrossRef]
21. Hebert, J.S.; Olson, J.L.; Morhart, M.J.; Dawson, M.R.; Marasco, P.D.; Kuiken, T.A.; Chan, K.M. Novel Targeted Sensory Reinnervation Technique to Restore Functional Hand Sensation after Transhumeral Amputation. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2014**, *22*, 765–773. [CrossRef] [PubMed]
22. De Nunzio, A.M.; Dosen, S.; Lemling, S.; Markovic, M.; Schweisfurth, M.A.; Ge, N.; Graimann, B.; Falla, D.; Farina, D. Tactile Feedback Is an Effective Instrument for the Training of Grasping with a Prosthesis at Low- and Medium-Force Levels. *Exp. Brain Res.* **2017**, *235*, 2547–2559. [CrossRef] [PubMed]
23. Schofield, J.S.; Shell, C.E.; Beckler, D.T.; Thumser, Z.C.; Marasco, P.D. Long-Term Home-Use of Sensory-Motor-Integrated Bidirectional Bionic Prosthetic Arms Promotes Functional, Perceptual, and Cognitive Changes. *Front. Neurosci.* **2020**, *14*, 496968. [CrossRef]
24. Rombokas, E.; Stepp, C.E.; Chang, C.; Malhotra, M.; Matsuoka, Y. Vibrotactile Sensory Substitution for Electromyographic Control of Object Manipulation. *IEEE Trans. Biomed. Eng.* **2013**, *60*, 2226–2232. [CrossRef] [PubMed]
25. Cipriani, C.; Segil, J.L.; Clemente, F.; Richard, R.F.; Edin, B. Humans Can Integrate Feedback of Discrete Events in Their Sensorimotor Control of a Robotic Hand. *Exp. Brain Res.* **2014**, *232*, 3421–3429. [CrossRef] [PubMed]
26. Witteveen, H.J.B.; Luft, F.; Rietman, J.S.; Veltink, P.H. Stiffness Feedback for Myoelectric Forearm Prostheses Using Vibrotactile Stimulation. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2014**, *22*, 53–61. [CrossRef]
27. Witteveen, H.J.B.; Droog, E.A.; Rietman, J.S.; Veltink, P.H. Vibro- and Electrotactile User Feedback on Hand Opening for Myoelectric Forearm Prostheses. *IEEE Trans. Biomed. Eng.* **2012**, *59*, 2219–2226. [CrossRef]
28. Marasco, P.D.; Hebert, J.S.; Sensinger, J.W.; Shell, C.E.; Schofield, J.S.; Thumser, Z.C.; Nataraj, R.; Beckler, D.T.; Dawson, M.R.; Blustein, D.H.; et al. Illusory Movement Perception Improves Motor Control for Prosthetic Hands. *Sci. Transl. Med.* **2018**, *10*, eaao6990. [CrossRef] [PubMed]
29. Peternell, G.; Penasso, H.; Luttenberger, H.; Ronacher, H.; Schlintner, R.; Ashcraft, K.; Gardetto, A.; Ernst, J.; Kropiunig, U. Vibrotactile Feedback for a Person with Transradial Amputation and Visual Loss: A Case Report. *Medicina* **2023**, *59*, 1710. [CrossRef]
30. Gardetto, A.; Baur, E.M.; Prahm, C.; Smekal, V.; Jeschke, J.; Peternell, G.; Pedrini, M.T.; Kolbenschlag, J. Reduction of Phantom Limb Pain and Improved Proprioception through a TSR-Based Surgical Technique: A Case Series of Four Patients with Lower Limb Amputation. *J. Clin. Med.* **2021**, *10*, 4029. [CrossRef]
31. Paredes, L.P.; Dosen, S.; Rattay, F.; Graimann, B.; Farina, D. The Impact of the Stimulation Frequency on Closed-Loop Control with Electrotactile Feedback. *J. Neuroeng. Rehabil.* **2015**, *12*, 35. [CrossRef] [PubMed]
32. Dosen, S.; Schaeffer, M.C.; Farina, D. Time-Division Multiplexing for Myoelectric Closed-Loop Control Using Electrotactile Feedback. *J. Neuroeng. Rehabil.* **2014**, *11*, 138. [CrossRef] [PubMed]

33. Dite, W.; Connor, H.J.; Curtis, H.C. Clinical Identification of Multiple Fall Risk Early after Unilateral Transtibial Amputation. *Arch. Phys. Med. Rehabil.* **2007**, *88*, 109–114. [CrossRef] [PubMed]
34. Karpman, C.; Le Brasseur, N.K.; De Pew, Z.S.; Novotny, P.J.; Benzo, R.P. Measuring Gait Speed in the Out-Patient Clinic: Methodology and Feasibility. *Respir. Care* **2014**, *59*, 531–537. [CrossRef] [PubMed]
35. Gaunaurd, I.; Kristal, A.; Horn, A.; Krueger, C.; Muro, O.; Rosenberg, A.; Gruben, K.; Kirk-Sanchez, N.; Pasquina, P.; Gailey, R. The Utility of the 2-Minute Walk Test as a Measure of Mobility in People with Lower Limb Amputation. *Arch. Phys. Med. Rehabil.* **2020**, *101*, 1183–1189. [CrossRef] [PubMed]
36. Schoppen, T.; Boonstra, A.; Groothoff, J.W.; De Vries, J.; Göeken, L.N.H.; Eisma, W.H. The Timed "up and Go" Test: Reliability and Validity in Persons with Unilateral Lower Limb Amputation. *Arch. Phys. Med. Rehabil.* **1999**, *80*, 825–828. [CrossRef]
37. Podsiadlo, D.; Richardson, S. The Timed "Up & Go": A Test of Basic Functional Mobility for Frail Elderly Persons. *J. Am. Geriatr. Soc.* **1991**, *39*, 142–148. [CrossRef]
38. Resnik, L.; Borgia, M. Reliability of Outcome Measures for People with Lower-Limb Amputations: Distinguishing True Change from Statistical Error. *Phys. Ther.* **2011**, *91*, 555–565. [CrossRef]
39. Sawers, A.; Kim, J.; Balkman, G.; Hafner, B.J. Interrater and Test-Retest Reliability of Performance-Based Clinical Tests Administered to Established Users of Lower Limb Prostheses. *Phys. Ther.* **2020**, *100*, 1206–1216. [CrossRef]
40. Carse, B.; Scott, H.; Davie-Smith, F.; Brady, L.; Colvin, J. Minimal Clinically Important Difference in Walking Velocity, Gait Profile Score and Two Minute Walk Test for Individuals with Lower Limb Amputation. *Gait Posture* **2021**, *88*, 221–224. [CrossRef]
41. Brooks, D.; Parsons, J.; Hunter, J.P.; Devlin, M.; Walker, J. The 2-Minute Walk Test as a Measure of Functional Improvement in Persons with Lower Limb Amputation. *Arch. Phys. Med. Rehabil.* **2001**, *82*, 1478–1483. [CrossRef] [PubMed]
42. Batten, H.R.; McPhail, S.M.; Mandrusiak, A.M.; Varghese, P.N.; Kuys, S.S. Gait Speed as an Indicator of Prosthetic Walking Potential Following Lower Limb Amputation. *Prosthet. Orthot. Int.* **2019**, *43*, 196–203. [CrossRef] [PubMed]
43. Roush, J.; Heick, J.D.; Hawk, T.; Eurek, D.; Wallis, A.; Kiflu, D. Agreement in Walking Speed Measured Using Four Different Outcome Measures: 6-Meter Walk Test, 10-Meter Walk Test, 2-Minute Walk Test, and 6-Minute Walk Test. *Internet J. Allied Health Sci. Pract.* **2021**, *19*, 7. [CrossRef]
44. Souza, J.M.; Cheesborough, J.E.; Ko, J.H.; Cho, M.S.; Kuiken, T.A.; Dumanian, G.A. Targeted Muscle Reinnervation: A Novel Approach to Postamputation Neuroma Pain. *Clin. Orthop. Relat. Res.* **2014**, *472*, 2984–2990. [CrossRef] [PubMed]
45. Valerio, I.L.; Dumanian, G.A.; Jordan, S.W.; Mioton, L.M.; Bowen, J.B.; West, J.M.; Porter, K.; Ko, J.H.; Souza, J.M.; Potter, B.K. Preemptive Treatment of Phantom and Residual Limb Pain with Targeted Muscle Reinnervation at the Time of Major Limb Amputation. *J. Am. Coll. Surg.* **2019**, *228*, 217–226. [CrossRef]
46. Mauch, J.T.; Kao, D.S.; Friedly, J.L.; Liu, Y. Targeted Muscle Reinnervation and Regenerative Peripheral Nerve Interfaces for Pain Prophylaxis and Treatment: A Systematic Review. *PM&R* **2023**, *15*, 1457–1465. [CrossRef]
47. Bell, J.C.; Wolf, E.J.; Schnall, B.L.; Tis, J.E.; Potter, B.K. Transfemoral Amputations: Is There an Effect of Residual Limb Length and Orientation on Energy Expenditure? *Clin. Orthop. Relat. Res.* **2014**, *472*, 3055–3061. [CrossRef]
48. Gailey, R.; Clemens, S.; Sorensen, J.; Kirk-Sanchez, N.; Gaunaurd, I.; Raya, M.; Klute, G.; Pasquina, P. Variables That Influence Basic Prosthetic Mobility in People with Non-Vascular Lower Limb Amputation. *PM&R* **2020**, *12*, 130–139. [CrossRef]
49. Ettema, S.; Kal, E.; Houdijk, H. General Estimates of the Energy Cost of Walking in People with Different Levels and Causes of Lower-Limb Amputation: A Systematic Review and Meta-Analysis. *Prosthet. Orthot. Int.* **2021**, *45*, 417–427. [CrossRef]
50. Jeans, K.A.; Browne, R.H.; Karol, L.A. Effect of Amputation Level on Energy Expenditure during Overground Walking by Children with an Amputation. *J. Bone Jt. Surg.* **2011**, *93*, 49–56. [CrossRef]
51. Göktepe, A.S.; Cakir, B.; Yilmaz, B.; Yazicioglu, K. Energy Expenditure of Walking with Prostheses: Comparison of Three Amputation Levels. *Prosthet. Orthot. Int.* **2010**, *34*, 31–36. [CrossRef] [PubMed]
52. van Schaik, L.; Geertzen, J.H.B.; Dijkstra, P.U.; Dekker, R. Metabolic Costs of Activities of Daily Living in Persons with a Lower Limb Amputation: A Systematic Review and Meta-Analysis. *PLoS ONE* **2019**, *14*, e0213256. [CrossRef] [PubMed]