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Oxygen consumption and gait dynamics in transfemoral bone-anchored prosthesis users compared to socket-prosthesis users: A cross-sectional study

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ABSTRACT

Background: A transfemoral bone-anchored prosthesis (BAP) is an alternative for the conventional socket-suspended prosthesis (SSP) in persons suffering from socket-related problems. In these persons, it has been demonstrated to reduce oxygen consumption during walking, which could be related to centre of mass (CoM) and trunk dynamics. However, it remains uncertain whether the same comparative findings are found in SSP-users without any socket-related problems.
Research question: Do oxygen consumption, CoM and trunk dynamics during walking differ between satisfied transfemoral SSP- and BAP-users and able-bodied individuals (AB); and are CoM and trunk dynamics and pistoning potential determinants of oxygen consumption?
Methods: Oxygen consumption was measured while participants walked on a treadmill at preferred speed, 30 % slower, and 30 % faster. At preferred speed, we also evaluated CoM deviation, root-mean-square values (RMS) of mediolateral (ML) CoM and trunk excursions, and pistoning. In the prosthetic users, we evaluated whether oxygen consumption, CoM and trunk dynamics, and pistoning were associated.
Results: We included BAP-users (n = 10), SSP-users (n = 10), and AB (n = 10). SSP-users demonstrated higher oxygen consumption, CoM and trunk RMS ML in comparison to AB during walking. BAP-users showed intermediate results between SSP-users and AB, yet not significantly different from either group. Greater CoM and trunk excursions were associated with higher oxygen consumption; in the SSP-users a greater degree of pistoning, in turn, was found to associate with larger trunk RMS ML.
Significance: Our results indicate that satisfied SSP-users have increased oxygen consumption compared to AB subjects and use compensatory movements during walking. An assessment of CoM and trunk dynamics, and pistoning during walking may be considered for evaluating whether an individual SSP-user could possibly benefit from a BAP, in addition to the currently used functional tests for evaluating eligibility. This might lead to a larger group of persons with a transfemoral SSP benefiting from this technology.

1. Background

After transfemoral amputation, a socket-suspended prosthesis (SSP) is commonly provided for ambulation. In recent years, osseointegration implants for suspension of a bone-anchored prosthesis (BAP) have been introduced as an alternative for the prosthetic socket [1–3]. Currently,

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only persons with socket-related problems (e.g. pressure pain and skin problems) affecting their daily activities and quality of life are eligible for a BAP [4], where provision of a BAP has been shown to resolve these problems and improve level of functioning and quality of life [5–12]. The observed improvements may be due to the resolution of pre-existing problems caused by SSP, yet it is unknown if these advantages can also be generalized to SSP-users who do not experience any socket-related problems.

One area where the additional advantages of a BAP may emerge concerns the metabolic cost of walking. Persons with a lower extremity amputation experience higher metabolic cost during walking than able-bodied individuals, particularly those with a transfemoral amputation [13,14]. In persons with transfemoral SSP, it was recently demonstrated that the use of compensatory mediolateral trunk movements presumably contributed to increased centre of mass (CoM) deviations and higher oxygen consumption during walking [15]. These mediolateral trunk movements are among other things assumed to help ensure sufficient toe clearance and stability of the prosthetic leg [16,17]. Greater lateral CoM movements are used to the overcome the absence of sufficient hip abductor strength to stabilize the pelvis over the base of support. Efforts to increase toe clearance are especially used to compensate for the effects of pistoning (i.e. vertical displacement) of the stump within the socket, which causes lengthening of the leg during the swing phase. The fixed connection of a BAP between the human skeleton and the external prosthetic parts may reduce the use of these compensation strategies and, consequently, influence gait efficiency and metabolic cost. Previous within-subject studies showed lower metabolic cost of walking following BAP surgery compared to preoperatively with SSP [18,19], yet it is unclear whether this effect was only due to resolution of socket-related problems or to potential additional benefits of the BAP itself. Hence, it is currently unknown whether CoM and trunk dynamics and metabolic cost of walking differ between satisfied SSP- and BAP-users.

The primary goal of this study was to determine whether the metabolic cost of walking, and CoM and trunk dynamics were different between active persons using a transfemoral BAP, those using an SSP, and able-bodied subjects. The secondary goal was to identify whether pistoning, and CoM and trunk dynamics relate to anticipated differences in oxygen consumption. With the fixed suspension of a BAP, it is hypothesised that less compensatory trunk movements (single and three dimensional) will be used and that, consequently, the metabolic cost of walking will be lower compared to SSP, while still showing greater CoM and trunk dynamics and higher metabolic cost compared to able-bodied individuals. Results of this study are expected to provide insight into whether a BAP may also benefit SSP-users without socket-related problems, which might improve functioning of a larger group of people, besides people with socket-related problems.

2. Methods

2.1. Participants

Three groups of individuals were included in the study: persons with a unilateral transfemoral BAP using a press-fit osteointegration implant, persons with a unilateral transfemoral SSP without socket-related problems, and able-bodied individuals (AB) as a control group. For all groups, a convenience sample was used aiming at 3 groups of 10 persons. Prosthetic users were eligible if they did not experience prosthesis-related problems at the time of the experiment, had been using a BAP of SSP for at least 2 years, and were considered active individuals (MFC-level K3–4). Exclusion criteria were vascular, neurological, or pulmonary diseases, or use of medication affecting balance or gait. All participants provided written informed consent before participating in the study. Study procedures were approved by the ethical committee CMO Arnhem-Nijmegen (2018–4919) and complied with the guidelines defined in the Declaration of Helsinki.

2.2. Study procedures

Study data were collected on two separate testing days. On the first testing day we assessed the functional capacity of the participants to be able to check that we included active individuals. For clinical assessment of the groups, participants performed functional tests, including the 2 min-walk-test (2MWT), the Timed-Up and Go (TUG) test, and the Brief Balance Evaluation Systems Test (Brief-BEST) [20–26]. Participants were given sufficient rest in between tests. In addition, participants completed the Questionnaire for Persons with a Transfemoral Amputation (Q-TFA) [27] and the Activities-specific Balance Confidence Scale (ABC). Able-bodied participants only completed the Mobility Score of Q-TFA.

Metabolic cost measurements started with recording the seated resting oxygen consumption for two minutes. After three minutes of familiarisation, participants walked on a treadmill for three blocks of four minutes: at self-selected preferred walking speed, 30 % slower, and 30 % faster, as done in previous studies [28,29]. Data were recorded using a breath-by-breath gas analyser (Cosmed Srl, Roma, Italy). The last minute of each block was used for analyses. In between the blocks, participants were seated until their heart rate approached the resting heart rate.

On the second testing day, kinematic data were collected while participants walked on a treadmill for 5 min at self-selected preferred walking speed. Reflective markers were placed on the body and equivalent anatomical position of the prosthesis according to the Vicon Plug-in Gait Full Body model [30] and were recorded using Vicon Motion Systems (Oxford, UK, 100 Hz).

2.3. Data analyses

The metabolic cost was calculated as the average oxygen consumption per meter, normalised by body weight (ML/kg/m) after subtraction of oxygen consumption during rest.

Standardized pre-processing pipelines of Vicon Nexus 2.10.1 were used to filter (Woltring filter, Mean Square Error=10) the motion capture data and reconstruct the positions of the CoM and the hip joint centre. Additional data analyses were done with Matlab 2019b (Mathworks Inc, USA).

CoM dynamics were evaluated in terms of both the CoM deviation [15] and the root-mean-square (RMS) values of mediolateral (ML) CoM movements. CoM deviation was defined as the percentage discrepancy between the true distance travelled in three dimensions by the CoM and the distance of a straight line between consecutive heel strikes (Fig. 1) [15]. Fontal plane trunk dynamics were evaluated with the RMS values of mediolateral sternum marker excursions. CoM and trunk RMS ML were calculated for each step and averaged.

Pistoning was defined as the change in upper-leg length (ΔULL) from initial contact of the prosthetic foot to toe-off of the contralateral foot, and calculated as the difference in absolute distance between the hip joint centre and the lateral knee marker.

2.4. Statistical analyses

For the statistical analyses, IBM SPSS Statistics 25 was used (IBM B. V., the Netherlands). Kolmogorov Smirnov tests were used to test whether data were normally distributed. As preferred walking speed on the treadmill was determined separately on both days, paired t-test was used to determine whether the walking speeds were significantly different on the two days. To test whether metabolic cost differed both between groups and walking speeds, a repeated-measures ANOVA was used. To evaluate between-group differences in the other variables of interest, we used one-way ANOVA with post-hoc independent t-tests for normally distributed variables, and Kruskal-Wallis with post-hoc Mann Whitney U tests for non-normally distributed variables.

To determine potential determinants of increased metabolic cost of

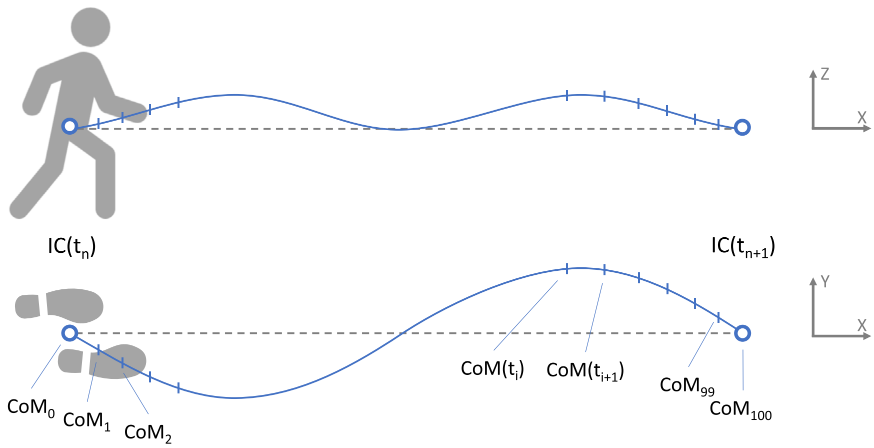

Fig. 1. Visual description of the CoM deviation from sagittal (above) and transverse (below) plane. The CoM deviation was calculated as the percentage discrepancy between the true distance travelled by the CoM and the distance of a straight line between consecutive heel strikes. The blue solid line represents the true trajectory of the CoM and the gray dotted line represents the straight line between the consecutive heel strikes.
Figure is adapted from Carse et al., 2020 [15].

walking in the combined group of SSP and BAP, correlations between CoM deviation, CoM RMS ML, trunk RMS ML, and oxygen consumption were evaluated. To determine the relationship with ΔULL, additional correlations were evaluated including only the SSP group. Due to limited sample size, a spearman correlations was used. Significance level for all tests was set at $\alpha = 0.05$. Post-hoc tests were Bonferroni corrected.

3. Results

We included BAP-users (n = 10), SSP-users (n = 10), and AB (n = 10), demographics are shown in Table 1. Statistics showed significantly longer residual limb length and higher weight of the prosthesis for the SSP compared to the BAP group. Note that this minor difference in prosthetic weight does not influence metabolic cost[31]. Functional test scores differed between groups, with both prosthetic user groups performing worse than AB subjects, while there were no significant differences between the SSP and BAP groups.

3.1. Metabolic cost

Preferred walking speed on the treadmill during the metabolic cost measurements was not significantly different between the groups (SSP: 0.9 ± 0.2 m/s, BAP: 0.9 ± 0.2 m/s, AB: 1.1 ± 0.2 m/s, H(2)= 5.517, p = 0.63). Overall, oxygen consumption in the SSP group was on average 49 % higher than in AB and 28 % higher than in the BAP group (group, F(2,27)= 4.164, p = .027), yet this difference only reached significance compared to AB (p = .026). Oxygen consumption between BAP and AB groups did not significantly differ (p = 1.00). Oxygen consumption differed significantly between walking speeds (F(1.412, 38.125)= 4.113, p = .037, Fig. 2), being 9 % higher during slow compared to preferred walking speed (p = .006). Oxygen consumption did not significantly differ between preferred and fast (p = 1.00), and slow and fast walking (p = .171). No interaction-effect was found (speed*group, p = .446).

3.2. CoM and trunk dynamics

For one participant with a BAP, CoM data could not be reconstructed due to occlusion of the C7 marker. Therefore, this participant was excluded from the CoM analyses.

CoM deviation in the SSP group presented a median of 1.6 % whereas the medians of the BAP and AB group were 1.2 %, yet between-group differences were not significant (H(2)= 2.142, p = .343, Fig. 3A). A main effect of group was found for CoM RMS ML (F(2,26)= 4.058, p = .029, Fig. 3B) and trunk RMS ML (H(2)= 9.479, p = .009, Fig. 3C). CoM RMS ML in the SSP group was on average 33 % higher than in AB person and 10 % higher than in the BAP group, being significantly different only in comparison to AB (p = .027). No significant difference was observed between the BAP and AB group (p = .295). Trunk RMS ML in the SSP group was on average 77 % higher than in AB and 25 % higher than in the BAP group, with post-hoc tests confirming a significant difference in comparison to AB (p = .012). The difference in trunk RMS ML between the BAP and AB groups did not reach significance (p = .069).

Presence of pistoning in the SSP group was confirmed in the statistical analyses (ΔULL (H(2)= 17.879, p < .001, Fig. 3D). Median ΔULL of the SSP group was 15 mm (range: 10–23 mm), which was significantly different from the BAP (median: 3 mm, p = <.001), and AB groups (median: 4 mm, p < 0.001).

3.3. Associations between oxygen consumption, CoM and trunk dynamics, and pistoning

The preferred walking speed did not differ between the two testing days (Z = −1.704, p = 0.88). In the combined group of prosthetic users, larger CoM deviation, CoM RMS ML, and trunk RMS ML were significantly associated with higher oxygen consumption (p < .01, Table 2). For the SSP group, larger ΔULL was significantly associated with larger trunk RMS ML (p < .025). Scatterplots showing the correlations can be found in the supplementary material.

4. Discussion

The study's primary goal was to identify whether oxygen consumption, CoM dynamics, and trunk dynamics differed between active persons using a transfemoral BAP or SSP, and able-bodied individuals. In agreement with our hypothesis, oxygen consumption and mediolateral CoM and trunk excursions were significantly larger in persons using an SSP compared to able-bodied individuals. Yet, the BAP group demonstrated in-between values that were not significantly different from either the SSP group or AB subjects. The secondary goal was to identify possible determinants of higher oxygen consumption in persons using a transfemoral prosthesis. Larger CoM deviations and mediolateral CoM and trunk excursions were associated with higher oxygen consumption during walking in prosthetic users. In turn, a greater degree of pistoning in persons using an SSP correlated with larger mediolateral trunk excursions.

As hypothesised, metabolic cost of walking was significantly higher (49 %) in persons using an SSP compared to AB subjects, which

Table 1
Means (SD) of participants' demographics and results of functional tests for all three groups.

	SSP (n = 10)	BAP (n = 10)	AB (n = 10)	Group statistics
Demographics				
Age (years)	56 (13)	59 (15)	57 (11)	H(2)= .360, p = .835
Sex (m/f)	5/5	6/4	5/5	
Length (cm)	176 (10)	175 (10)	178 (7)	F(2,27)= .284, p = .755
Weight (kg)	80 (20)	77 (13)	76 (12)	F(2,27)= .217, p = .806
Cause of amputation	8 tr, 1 ca, 1 inf	5 tr, 4 ca, 1 con		
Years since amputation (years)	27 (14)	25 (17)		t(18) = −.258, p = .799
Years since OI operation (years)		5 (2)		
Weight of prosthesis (kg)	4.3 (1.0)	3.5 (0.3)†		t(10.5) = −2.540, **p = .028**
Residual limb length (cm)	21.9 (3.5)	15.3 (3.8)†		t(18) = −3.987, **p = .001**
Prosthetic knees	5x Genium, 2x C-Leg, 2x VGK, 3R106 Pro	6x C-Leg, Rheo XC, Freedom Flie, VGK, 3R80		
Functional tests				
2MWT (m)	162 (29)+	155 (22)+	228 (15)	F(2,27)= 30.940, **p < .001**
TUG (sec)	9.1 (2.9)+	8.5 (1.7)+	5.6 (0.7)	H(2)= 17.158, **p < .001**
Brief-BEST	18 (3)+	16 (4)+	23 (1)	H(2)= 19.625, **p < .001**
Q-TFA Prosthetic user score (%)	96 (5)	98 (4)		Z = −.951, p = 481
Q-TFA Mobility score (%)	88 (7)+	88 (7)	94 (3)	H(2)= 6.200, **p = .045**
Q-TFA Problem score (%)	11 (5)	10 (9)		t(18) = .293, p = .773
Q-TFA Global score (%)	77 (9)	73 (12)		Z = −.712, p = 529
ABC (%)	90 (11)	90 (9)	97 (3)	F(2,27)= 2.573, p = .095

SSP: Socket-suspended prosthesis; BAP: Bone-anchored prosthesis; AB: Able-bodied individuals; m: male; f: female; OI: Osseointegrated implant; tr: trauma; ca: cancer; inf: infection; con: congenital; 2MWT: 2-minute walk test; TUG: Timed-up and go; Brief-BEST: Brief Balance Evaluation Systems Test; Q-TFA: Questionnaire for persons with transfemoral amputation; ABC: Activities-specific Balance Confidence Scale; p-values are displayed in bold when indicating a significant difference between the groups; † indicates significant difference from SSP groups; + indicates significant difference from AB

difference compares closely with ~50 % higher metabolic cost as reported in previous studies [15,32]. Persons using a BAP on average used 28 % less oxygen than those using an SSP. While this difference failed to reach significance, previous research suggested a 16 % difference in metabolic cost can be considered clinically relevant [33,34]. This may indicate a clinically relevant benefit of using a BAP compared to an SSP regarding metabolic cost, although an average 16 % higher metabolic cost still persisted in persons using a BAP as compared to AB subjects. Additionally, it should be noted that persons using an SSP displayed large variations in metabolic cost with three individuals exhibiting noticeably higher metabolic cost.

CoM and trunk excursion for the SSP group were significantly larger than for AB subjects, displaying on average 33 % greater CoM and 77 % greater trunk movement in mediolateral directions, whereas the BAP group demonstrated intermediate results with 10 % smaller CoM and 25 % smaller trunk excursions as compared to the SSP group (not significantly different). Similar intermediate results were found in a study that reported within-subject differences following BAP surgery [35]. These authors reported an improvement in hip extension and anterior pelvic tilt when using a BAP compared to using an SSP, whereas the values were still different from AB subjects. These findings may point at reduced use of compensation strategies during walking when using a BAP as compared to an SSP. Although the CoM deviation values in the current study showed a similar pattern with the BAP groups displaying 25 % less CoM deviation compared to the SSP group, between-group differences were not statistically significant. Yet, the median CoM deviation values of the SSP (1.6 %) and BAP (1.2 %) groups may demonstrate that our population moderately uses compensatory movements, as previous research reported an average 2.0 % CoM deviation in persons using an SSP [15].

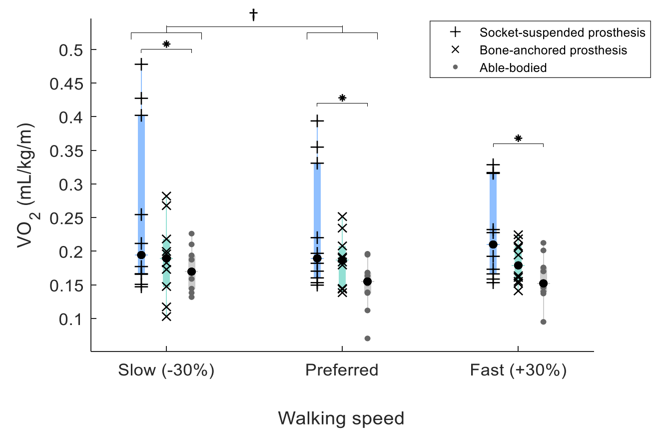

Fig. 2. The results of the metabolic cost measurements presented in a boxplot over three speed levels for all three groups. Grey boxplots present the data distribution from the 25th to the 75th percentiles, and the black circle indicates the median. Each individual data point represents one participant. SSP: Socket-suspended prosthesis; BAP: Bone-anchored prosthesis; AB: Able-bodied individuals; * indicates significant difference between groups ($p < .05$) † indicates significant difference between speeds ($p < .05$);.

Greater CoM and trunk dynamics were found to correlate with higher oxygen consumption in the combined group of prosthetic users. These compensation strategies may partly explain the higher metabolic cost of walking in persons using transfemoral prosthesis, which interpretation is in line with previous literature [15,36]. In the SSP group, a greater degree of pistoning was found to be linked to larger mediolateral trunk excursions, presumably contributing to higher oxygen consumption while walking. Interestingly, two of the three SSP-users with higher oxygen consumption also exhibited the highest amount of pistoning, and mediolateral trunk excursion. Indicating the presence of (substantial) pistoning may induce greater use of compensation strategies, so by extension, resolution of pistoning by the fixed suspension of a BAP might be beneficial for those individuals. However, it should be noticed that our BAP group still displayed greater CoM and trunk movements compared to AB subjects. Due to absence of muscles in the prosthetic leg and atrophy of the hip muscles – as commonly observed after long-term use of a prosthesis [12,16,17,37] – additional trunk movements may be needed to bring the CoM towards the prosthetic leg and stabilise the pelvis during the stance phase of the prosthetic leg. Alternatively, these movements may be related to persistent use of compensation strategies learned while using an SSP, which may no longer be needed with the fixed suspension of the BAP. Hence, it remains to be determined whether the additional CoM and trunk movements in persons using a BAP should be considered adaptive or maladaptive.

Unlike BAP users showing intermediate values between the SSP users

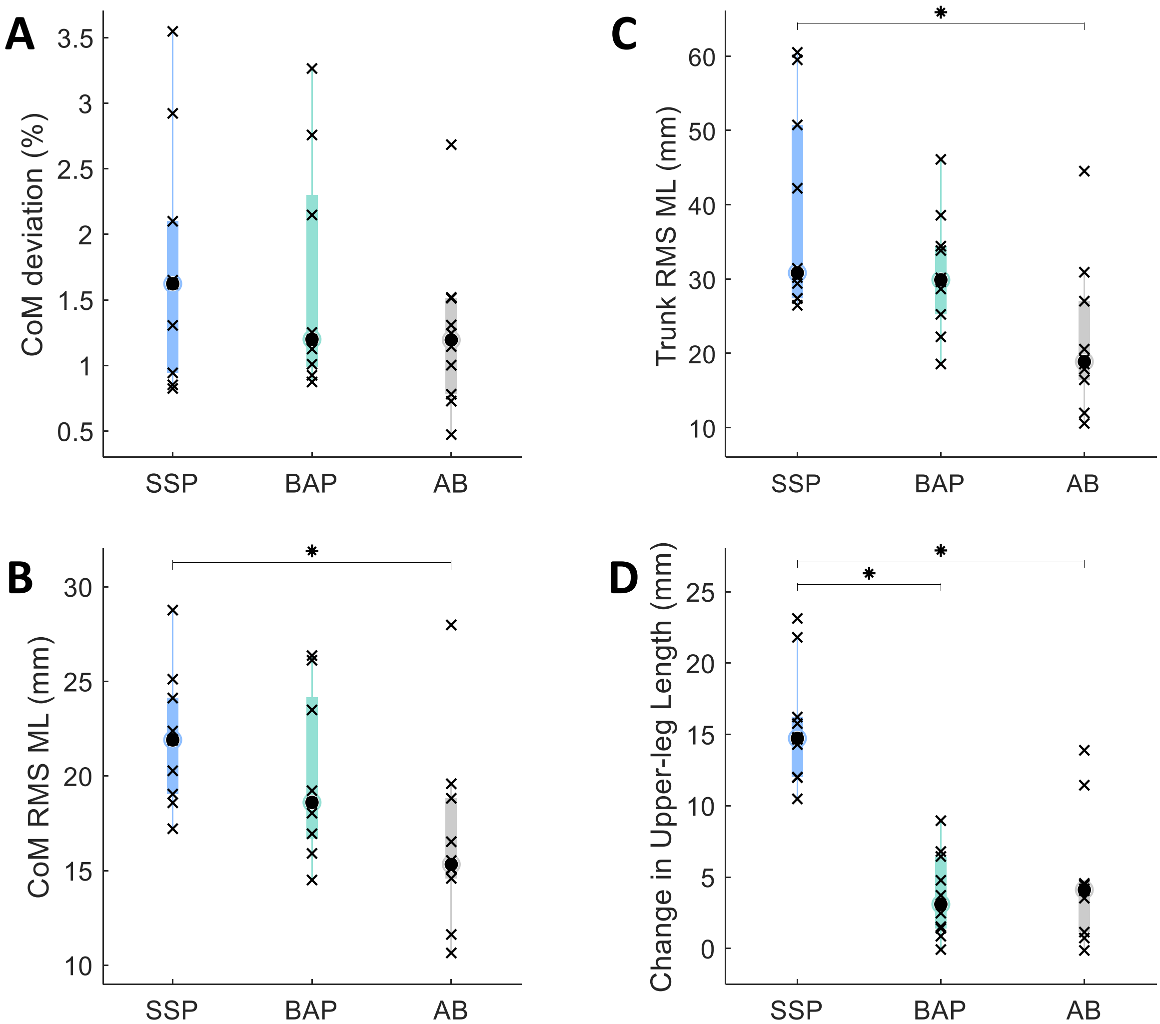

Fig. 3. The results of the gait measurements including CoM deviation (A), CoM RMS ML (B), trunk RMS ML (C), and ΔULL (D) for all three groups. Grey boxplots present the data distribution from the 25th to the 75th percentiles, and the black circle indicates the median. Each individual data point represents one participant. CoM: Centre of mass; RMS ML: Root-mean-square mediolateral; SSP: Socket-suspended prosthesis; BAP: Bone-anchored prosthesis; AB: Able-bodied individuals; * indicates significant difference ($p < .05$);.

Table 2
Spearman correlations between oxygen consumption, CoM deviation, CoM RMS ML, and trunk RMS ML for SSP and BAP combined, and with ΔULL for SSP.

	SSP+BAP			SSP
	CoM deviation	*CoM RMS ML*	*Trunk RMS ML*	*ΔULL*
Oxygen consumption	$r_s(19) = .756$*	$r_s(19) = .625$*	$r_s(20) = .740$*	$r_s(10) = .418$
CoM deviation		$r_s(19) = .828$*	$r_s(19) = .693$*	$r_s(10) = .564$
CoM RMS ML			$r_s(19) = .782$*	$r_s(10) = .455$
Trunk RMS ML				$r_s(10) = .697$*

CoM: Centre of mass; RMS ML: Root-mean-square mediolateral; ΔULL: Change in upper-leg length; SSP: Socket-suspended prosthesis; BAP: Bone-anchored prosthesis; * indicates significance

and AB subjects regarding oxygen consumption and CoM and trunk dynamics, no such pattern was observed in the functional outcomes. BAP and SSP users had roughly equivalent scores; both groups mostly performed worse than AB subjects. Nonetheless, when comparing the functional outcomes of the BAP and SSP group to values reported in the literature of BAP- and highly active SSP-users, it can be concluded that our participants had a high level of functioning [5,8,12,38,39]. For example, our population needed on average 9.1 s in the SSP group and 8.5 s in the BAP group to complete the TUG, which is comparable to the TUG values of K4-level SSP walkers found in previous studies (range: 7.92–10.98 s, mean: 9.45 s) [39]. Currently, these functional tests are used to evaluate the level of functioning before and after receiving a BAP. Our findings indicate that these functional tests are seemingly not sensitive to the subtle differences in prosthetic users with a high level of functioning. Hence, evaluating CoM and trunk dynamics in the frontal plane and pistoning during walking may provide additional information on whether satisfied SSP users could benefit from an optimisation of socket fit, or determine whether a BAP may be considered. Therefore, these parameters may be considered as part of a core-set of outcome measures of BAP.

A limitation of the study was its cross-sectional design, limited sample size, limited demographic variance, and separate collection of oxygen consumption and kinematic data. The use of a cross-sectional design might introduce potential selection biases. BAP-users underwent a surgical intervention, which may have negatively affected their fitness, but also received additional training which may have limited their use of compensation strategies. Yet, these aspects will have had limited influence on the current outcomes, as the BAP surgery or amputation had taken place at least 2 years before inclusion. The main strength of the study was the inclusion of highly active and satisfied prosthetic users. The absence of confounding effects of prosthesis-related problems allowed making inferences on the potential added benefits of a BAP for a subset of persons using an SSP (i.e. those with greater degrees of pistoning and larger trunk excursions). However, total elimination of confounding effects cannot be guaranteed. In addition, limited sample size may have resulted in false-negative (type II errors) or false-positive results (type I errors). Further studies with larger sample sizes are needed to provide conclusive evidence regarding between-group differences.

5. Conclusions

The current study confirms that persons using an SSP have increased oxygen consumption, CoM, and trunk dynamics than able-bodied individuals when walking. Persons using a BAP showed non-significantly different intermediate results, indicating that some active persons with an SSP without socket-related problems may potentially benefit from a BAP for partly reducing compensatory trunk movements presumably due to the fixed suspension and, may consequently, reducing oxygen consumption during walking. This may particularly apply to persons with an SSP who experience greater degrees of pistoning. Clinically, an evaluation of pistoning, CoM, and trunk dynamics during walking may be considered for determining whether individuals using an SSP are eligible for a BAP, in addition to the currently-used criteria.

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Declaration of Competing Interest

The authors declare that they have no conflict of interests.

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None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.04.008.

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