Full length article

Energy cost of walking in transfemoral amputees: Comparison between Marlo Anatomical Socket and Ischial Containment Socket

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ABSTRACT

Objective: To compare energy cost of walking (ECW) and prosthesis-related perceived mobility with the Marlo Anatomical Socket (MAS®) and the Ischial Containment (IC) Socket.
Method: Transfemoral (TF) amputees were enrolled in the study. ECW tests were conducted inside, in a hallway with a regular floor surface. Subjects had to walk back and forth on a 61 m linear course at their own self-selected speed. Metabolic and heart rate data were collected during the walking test using a portable gas analyzer. All measurements were made at steady state (SS). The tests were performed first using the IC socket and then after 30 days of MAS® use; the last test was carried out after 60 days of MAS® use. The amputees were also administered the Prosthetic Evaluation Questionnaire Mobility Section (PEQ MS) at the first and the last test to assess perceived potential for mobility using the prosthesis.
Results: Seven long-term prosthesis users were analyzed. Their mean age was 33.9 ± 9.3 years; all were employed, active, and used IC sockets. At the third walking test, the ECW with the MAS® was significantly lower than that with the IC socket ($p = .016$). PEQ MS data also improved significantly at the last evaluation ($p < .018$).
Conclusion: Results suggest that using the MAS®, lowering the ECW and improving PEQ MS, could be a valid prosthesis design for active TF amputees compared to their usual IC socket.

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1. Introduction

As transfemoral (TF) amputees have a greater energy cost of walking (ECW) than intact individuals and individuals with a lower amputation level [1], prosthesis design is aimed at improving their walking efficiency.

The socket shape most used by TF amputees is that of the Ischial Containment (IC) Socket. It has an elliptical-shaped brim, a wide antero-posterior and a narrow medio-lateral size with a high lateral brim (Fig. 1, left panel). It is also termed CAT CAM (Contoured Adducted Trochanteric Controlled Alignment Method) or "ischial ramal weight bearing socket", because it encloses the ischial tuberosity and the ramus within the socket. For more than two decades, the IC socket supplanted the quadrilateral socket, also because it reduces the energy cost of walking [2]. Then, about ten years ago Marlo Ortiz Vasquez developed the Marlo Anatomical

Socket (MAS®) for TF amputees (Fig. 1, right panel). According to Trower [3], the MAS® seems to provide greater ischial containment and mediolateral stability than other sockets; it also reduces trim lines and improves hip range of motion (ROM).

The main feature of the MAS® design is that the Ischium and gluteus maximum are not included in the socket because of the lowered posterior shelf. In TF amputees, IC socket interference limits the physiological ROM [4]. Michaud et al. [5] found that at self-selected speeds TF amputees lift the pelvis on the swing side while walking. This compensatory motion, known as hip hiking, may require additional metabolic energy to lift body mass against gravity, thus reducing gait efficiency.

Due to its characteristics, the MAS® should reduce ECW and improve prosthesis-related perceived mobility compared with the IC socket. Assessing ECW is a functional evaluation method used to evaluate physiological response to exercise. In the field of rehabilitation, this method is used to quantify the influence of disability on walking capacity [6]. The ECW is commonly used to quantify the actual energy demand during walking [1,7–10] and to compare the efficiency of different types of prostheses [11–16]. ECW evaluation is an important clinical outcome measure. In fact, ECW greatly influences the individual's ability to use the prosthesis and to walk, thus affecting autonomy level and quality of life.

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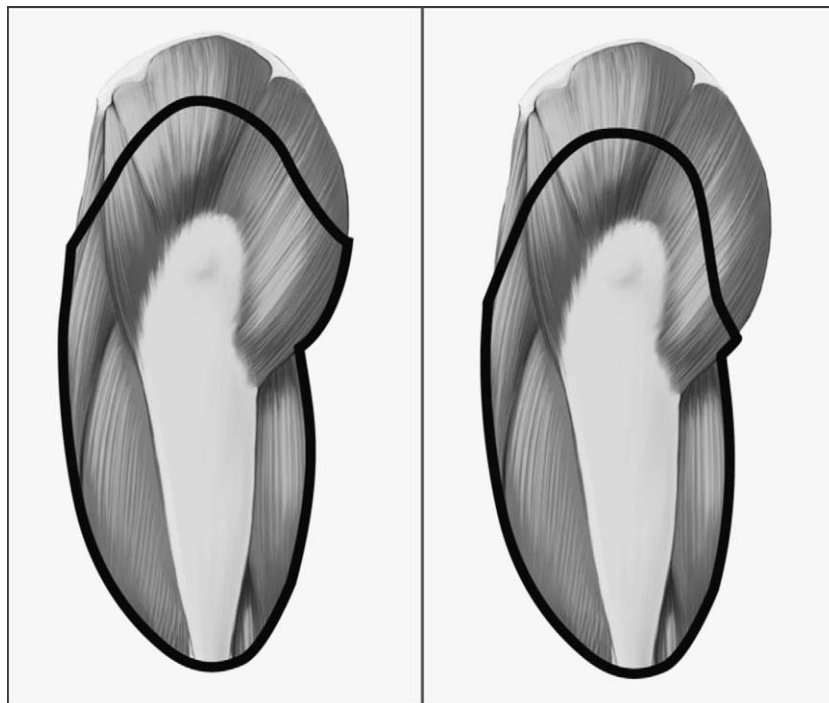
Fig. 1. Left panel: Ischial Containment Socket's shape; right panel: Marlo Anatomical Socket's shape. The anterior and posterior trim lines in MAS are lower than in IC socket: inferior to the anterior superior iliac spine and at the gluteus fold level respectively.

To our knowledge, no data are reported in the literature on TF amputees' ECW using the MAS®. Therefore, the main aim of the present study was to compare the ECW of these patients when they were wearing the MAS® and the IC socket.

To verify whether MAS® improves gait efficiency in TF amputees, ECW tests were first administered when they were wearing the IC socket and then (after a 30-day and a 60-day acclimation period) when they were wearing the MAS®. The length of the acclimation periods was established on the basis of Datta et al.'s results [17]; these authors reported that trans-tibial amputees needed a minimum of 6 weeks to become accustomed to a socket. As there are no data in the literature on the acclimation period needed by TF amputees following a change of socket (i.e. to one with a different shape), for our purposes we chose 30-day and 60-day acclimation periods.

Another aim of the study was to determine whether using the MAS® improves prosthesis-related perceived mobility more than using the IC socket. For this purpose, each subject completed the Italian version of Ferriero et al.'s [18] Prosthetic Evaluation Questionnaire Mobility Section (PEQ MS) at the first and the last evaluation.

2. Materials and methods

2.1. Subjects

To participate in the study, subjects had to meet the following inclusion criteria: (a) unilateral amputation of lower limb at above-knee level; (b) use of a prosthesis for at least 1 year; (c) ability to walk without aids; (d) a K level of three or more [19]; (e) pneumatic or hydraulic unlocked prosthetic knee; (f) the absence of pathological stump conditions counteracting prosthesis use; (g) the absence of functional impairments of the sound limb; (h) the absence of mental/cognitive or other significant disorders. Twelve participants were enrolled in the study. All had been using the same prosthesis daily for at least 5 years; that is, they had been using the prosthesis continuously for 5–9 h a day, were able to walk without aids and were employed. The enrolled participants gave their informed consent to participate in the study, according to the guidelines of the local ethics committee that approved the study.

2.2. ECW data collection

The subjects were requested to walk at their own self-selected walking speed (SSWS) up and down a 61 m linear course in a hallway with a regular floor surface. While they performed the walking test, subjects wore a breath-by-breath portable gas analyzer (K4 b^2, Cosmed, Italy) and a heart rate (HR) monitor (Polar Electro Oy, Finland). The K4 b^2 was calibrated before every test according to the manufacturer's procedures. The following parameters were recorded: oxygen consumption (V'O$_2$ ml/kg/min), carbon dioxide production (V'CO$_2$ ml/kg/min), respiratory exchange ratio (RER, V'CO$_2$/V'O$_2$) and walking speed (m/min). Test duration (i.e., walking up and down the 61 m linear course) was at least 7 min to allow the participants to reach and maintain the steady state (SS) condition of heart rate and metabolic parameters. The telemetry system of the K4b^2 allowed verifying achievement of the SS in real time; then the test was continued for about 4 min. SS was defined as follows: the condition in which after about 3 min of exercise, at a constant and submaximal workload, oxygen consumption rate meets the energy demand. This is the condition in which oxygen consumption, respiratory and heart rate maintain a plateau. Mean walking speed was calculated as the ratio of distance to time; the walking speed obtained in the last 2 min of data collection was considered.

Steady state data (i.e. V'O$_2$, V'CO$_2$, RER, HR, walking speed) was calculated as the mean value of data collected in the last 2 min of data recording. Then ECW was calculated as follows: V'O$_2$ (ml/kg/min)/walking speed (m/min).

As an index of the relative exercise intensity of walking, the percentage of age-predicted maximum heart rate (%APMHR) was determined as follows: (walking HRss/220 − age) × 100 [20].

Participants performed the walking test three times. The first time, they wore their usual IC socket. Then, the same experienced prosthetist constructed the MAS® for all participants, maintaining all other prosthesis components unchanged. Each participant had to visit the prosthetist 3–5 times over a period of 2–3 weeks to obtain the optimal socket fit. After 30 days of daily MAS® use, participants performed the second walking test and after 60 days, the third walking test. All tests were conducted in the same environment in the morning. Participants wore the same kind of clothes and shoes for all tests.

Each participant was also administered Ferriero et al.'s [18] Italian version of the Prosthetic Evaluation Questionnaire Mobility Section (PEQ MS) at the first and the last evaluation.

PEQ-MS is a self-report scale that investigates the locomotor capabilities of people with lower limb amputation wearing prostheses [21]. PEQ MS is composed of two scales: eight ambulation items and five transfer items (e.g. getting in and out of a car, sitting down and getting up from the toilet, sitting down and getting up from a low or soft chair, etc.). PEQ MS is a retrospective questionnaire that evaluates participants' perceived potential for mobility using prosthetic devices over the

Table 1
Subjects' characteristics and prosthetic components used.

Subjects	M/F	Age (years)	Body mass (kg)	Height (cm)	Time since amputation (years)	Socket	Knee	Foot
1	M	28	75	180	9	IC/MAS	C-LEG	Trustep
2	M	44	81	185	6	IC/MAS	C-LEG	Trustep
3	M	46	91	184	21	IC/MAS	C-LEG	Vari-Flex Low Profile
4	M	25	69	180	2	IC/MAS	C-LEG	Trustep
5	M	28	70	175	10	IC/MAS	Mauch® hydraulic system	Vari-Flex Low Profile
6	M	41	77	174	26	IC/MAS	C-LEG	1C40
7	F	25	78	164	3	IC/MAS	hydraulic single axis 3R45	Vari-Flex Low Profile
	Mean	33.9	77.3	177.4	11.0			
	SD	9.4	7.4	7.2	9.1			

Table 2
Functional data during walking tests.

Walking Test	HR rest (bpm)	SSWS (m/min)	HR ss (bpm)	%APMHR	V'O$_2$ ss (ml/kg/min)	ECW (ml/kg/m)	RER ss
I	81.9 ± 11.8	65.9 ± 4.7	124 ± 23.6	67 ± 12	17.7 ± 3.8	.26 ± .06	.82 ± .09
II	80.7 ± 8.2	68.2 ± 9	121 ± 14.8	65 ± 9	16.9 ± 2.3	.24 ± .05	.83 ± .07
III	79.9 ± 9.3	70 ± 6.5	120 ± 15.5	65 ± 8	16.3 ± 1.5	.23 ± .044[*]	.84 ± .05

Walking test I: fitting an Ischial Containment Socket; test II and III: fitting MAS®.
HR: heart rate; SSWS: self selected walking speed; %APMHR: percentage of age predicted maximum heart rate; V'O$_2$: oxygen consumption; ss: steady state; ECW: energy cost of walking; RER: respiratory exchange ratio; bpm: beats per minute.
[*] I vs III ($p = .016$).

preceding 4 weeks. Answers are scored using a visual analogue scale, that is, on an 11-step (0–10) numerical rating scale. The end-points are labeled "0 = unable, or hardly able at all (less than 5% of ability)" and "10 = no problems or almost completely able (more than 95% of ability)". A summary score was calculated as the arithmetical mean of scores on all questions at both the first and the last evaluation [18].

2.3. Statistical analysis

All data were expressed as means and standard deviations. Due to the small sample size, statistical analysis was performed with non-parametric tests. To compare the data of the three evaluation tests, Friedman's test was used. When Friedman's test was statistically significant, a non-parametric post hoc multiple comparison was performed using Wilcoxon's test (setting the critical adjusted α value using Bonferroni's inequality).

Wilcoxon's test was used to compare PEQ MS data (i.e. the arithmetical mean of scores on all questions from both evaluations). A probability value of .05 was set as the level of statistical significance. Data analysis was performed using SPSS software version 14.0.

3. Results

Five of the 12 enrolled participants did not complete the study for reasons unrelated to health: one moved too far away to participate, two had family problems, and two had difficulty obtaining permission to leave work to participate in the study. Seven subjects completed the study; their characteristics are reported in Table 1.

Except for one case of amputation due to bone cancer, the other six subjects were post-traumatic amputees. Table 2 reports metabolic, HR, and ECW values for each test.

As reported in Table 2, V'O$_2$ss, HRss, %APMHR as well as SSWS showed a trend towards improvement in the three tests; the ECW lowered progressively with MAS® use and was significantly lower at the last than the first walking test.

Table 3 reports the PEQ-MS data, which improved significantly at the last evaluation compared with the first evaluation, when the IC socket was used.

4. Discussion

The goal of prosthesis design is to create a socket that allows for a range of motion (i.e. the physiological arc of motion of a joint)

that is as close as possible to the physiological one at the hip and that does not interfere with muscle activity. A socket with these characteristics should reduce energy expenditure and, thus, improve amputees' walking efficiency (i.e. by reducing ECW). The more physiological range of motion of MAS® is due to the fact that the ischium is not encapsulated in the socket as it happens with the IC. The anterior and posterior trim lines of the MAS® are lower than those of the IC socket, that is, they are inferior to the anterior superior iliac spine and at the level of the gluteus fold, respectively. This allows for greater ROM and consequently improves function because the entire ROM of the hip joint is exercised during walking [22].

In this study, our main aim was to quantify TF amputees' ECW when they wore two different kinds of sockets (IC and MAS®) to determine whether MAS® would improve gait efficiency after a 30-day and a 60-day acclimation period. We also aimed to assess participants' potential and perceived mobility by having them completed the PEQ MS at the first and the last evaluation. Transfemoral amputee's ECW was assessed with over ground walking tests at a Self-Selected Walking Speed (SSWS). This test was chosen because of the findings of Teixeira-Salmela et al.'s study [23] that at natural or much faster walking cadence the lower limb muscles work at a lower percentage of their maximum capacity than at a slower cadence (i.e., 60–80 steps/min), thus

Table 3
PEQ-MS scores for each subject and statistical analysis. All data are reported as mean and standard deviation. Scores I relate to the IC socket, before MAS® delivery, scores II are after 60 days of MAS® use.

Subjects	Scores I	Scores II
1	5.9 ± 1.1	7.1 ± 1.2
2	9.3 ± 1.3	9.5 ± 1.2
3	6.5 ± .7	7.6 ± .9
4	6.3 ± .9	7.9 ± .8
5	6.8 ± 1.8	8.5 ± 2.4
6	6.5 ± .7	8.8 ± 2.1
7	5.3 ± 2.4	7.6 ± 2.4
Mean	6.7	8.1[*]
SD	1.3	.8

[*] Scores I vs scores II: $p = .018$.

optimizing energy consumption during gait. SSWS is a well-known marker of gait performance and is widely used to evaluate locomotor skills. Also, according to Kang and Dingwell [24] SSWS has been, in recent studies, preferred to fixed speed, since everyone has their own walking speed. In recent gait studies, SSWS was investigated by treadmill walking [25,26] because it allows for a multiple gait cycle recording at fixed speed, it can provide body weight support and, finally, makes it possible to perform walking tests in a small laboratory [27]. The over ground walking test is preferable to that on a treadmill, because the latter produces an overestimation of ECW [28] and does not indicate the individual's real daily walking capability [29]. An analysis of transfemoral amputees' ECW over time was carried out for the MAS® but not for the IC socket, because all amputees were long-term prosthesis users (i.e. they had been wearing the IC socket for more than 2 years and had a stabilized gait pattern). Therefore, an IC socket analysis would not have revealed any differences. Due to lack of data on the acclimation period needed by TF amputees to become used to a new socket, we chose a 30-day and a 60-day acclimation period based on physician expertise.

In the three walking tests, the %APMHR and RERss values indicated submaximal effort. Furthermore, as expected, none of the SSWS tests induced fatigue; this was verified by asking participants whether they were tired at the end of the test. HRss, %APMHR, V'O$_2$ ss and SSWS showed a non significant trend towards improvement in the three tests probably because all TF amputees who participated in this study already had fast walking speed even at the first evaluation. As the amputees did not change their life style during the study, it was not surprising that HR and V'O$_2$ showed only a trend towards improvement. On the contrary, ECW data showed statistically significant improvement of TF gait efficiency when the MAS® was used rather than the IC socket (only on the last test). When we compared the ECW and SSWS values of the present study with those of our previous study [29], we found that the current ECW value was almost half the previous one and that the SSWS was about twice. This is probably because in our previous study [29] the patients were short-term prosthesis users (about 2 months), walking aid users, had been amputated for peripheral vascular disease and had a mean age of 61 ± 11 years. By contrast, the TF amputees in the present study were long-term prosthesis users, traumatic amputees, younger and physically more active. This interpretation is further supported by Orendurff et al.'s [30] data. These authors reported ECW and SSWS values similar to ours and derived from TF amputees comparable to ours. As reported in Table 1, the subjects used different prosthesis components. This did not represent a confounding factor, however, because our study had a within subject design, which is not affected by differences across subjects and is more suitable for detecting differences between prosthetic devices. The highest ECW value was recorded in the first walking test with the IC socket; the lowest ECW value was recorded after 60 days of MAS® use. Considering that the only prosthesis component which changed in the three walking tests was the socket and that the amputees were requested to maintain their life style (physical activity, sports, nutrition) unchanged over time, we can affirm that in our TF amputees reduced ECW was ascribable to MAS® use. Significant ECW improvement was observed only after 60 days of MAS ® use, probably because this amount of time was needed for the stump to reach the new shape, for the subject to acclimate to the new socket and to walk comfortably with the new gait pattern (i.e. greater hip extension during the terminal stance phase of gait). PEQ scores improved significantly and participants noted that the greatest benefit derived from using the MAS® was "walking up a steep hill" and "sitting down and getting up from a low or soft chair". The first benefit was probably due to the possibility of greater hip extension, the second to greater comfort in sitting through the cut lines of the socket, which allowed them to sit leaning on the gluteus maximus

muscle instead of on the socket, as occurs when using the IC socket. Furthermore, our PEQ MS results allow us to affirm that the MAS® produced improved perception of walking capacity in our TF amputees.

Although MAS® seems to improve gait efficiency, we are unable to explain the underlying biomechanical mechanism. Human locomotion is a combination of step length, frequency and width, which minimizes energy expenditure. At a given walking speed, each deviation from the physiological pattern of one or more of these biomechanical parameters produces an increase in energy expenditure. Therefore, knowledge of which parameters are implicated and how the socket affects them may help us improve socket design. For this reason further more focused studies are needed.

5. Study limitations

Some limitations of our study should be noted. First, the sample of subjects was relatively small. This was due to difficulty in recruiting subjects willing to change the components of their usual prosthesis and/or to adhere to a study requiring long-term participation. Indeed, the latter increases dropout rates due to changes in social or factors. In particular, the study population included only amputees of a given functional status, who were active and had a young mean age. Therefore, the results cannot be generalized across a broader population. Furthermore, the small sample size may not have provided adequate power to detect smaller differences between the two sockets (e.g. the statistical power for SSWS was .68). Again, additional studies carried out in larger samples are needed to determine whether the highlighted trends were statistically significant.

Finally, the acclimation periods in this study were 30-days and 60 days. This may not have been enough time for participants to acclimate to the new socket. But, due to the lack of data in the literature on this population we chose the acclimation period from data on transtibial amputees [17].

6. Conclusions

For physically active TF amputees (such as ours), a socket that allows a range of joint motion as close as possible to the physiological one, with minimal energy expenditure, should be the goal of prosthesis design. The results of the present study suggest that MAS® can help us to reach this goal. Finally, further studies are needed to investigate ECW and prosthesis-related perceived mobility in older and/or non-active TF amputees.

Conflict of interest statement

No support was received in the form of grants, equipment, or drugs. No commercial entity with a direct financial interest in the results of the research supported this article, or has or will confer a benefit upon the author(s) or upon any organization with which the author(s) is/are associated.

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