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The CAT-CAM socket and quadrilateral socket: a comparison of energy cost during ambulation

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Abstract

Twenty unilateral trans-femoral amputees fitted with either the Contoured Adducted Trochanteric-Controlled Alignment Method (CAT-CAM) socket (n=10) or the quadrilateral (QUAD) socket (n=10), and a "non-amputee" control group (n=10) participated in the study. Subjects meeting the following criteria were studied: healthy males between the ages of 18 and 55 years, amputation due to non-vascular pathology, an unaffected sound limb, at least six months use of the test prosthesis, and a minimal stump length of 15 cm. Subjects ambulated in two randomized trials separated by 20 minutes of rest at 2 assigned speeds: a pace reflecting normal walking speed (97 m/min=2.5 mph) or a slower speed (48.5 m/min=1.25 mph). Heart rate (HR) and Oxygen uptake (VO_2) measured during steady state walking were analyzed via two-way ANOVA. Differences among means were further analyzed using Tukey post hoc and simple effects tests. Significant differences were observed between the control group and CAT-CAM subjects with respect to VO_2 ($p<0.05$) and HR ($p<0.01$) at the slower speed. The control group and subjects using the QUAD socket also differed with respect to VO_2 ($p<0.01$) and HR ($p<0.01$) at the slower pace. Faster pace required more energy expenditure ($p<0.01$) and produced higher HR ($p<0.01$) than slower speeds. At faster pace, a significantly higher energy expenditure in the QUAD than the CAT-CAM group was observed ($p<0.01$). It is concluded that ambulating at normal pace using the CAT-CAM socket design uses less energy than when using a QUAD socket design.

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Introduction

Interest in lower limb prosthetic research has recently focused on reducing energy expenditure during ambulation. Different types of prostheses have been designed for trans-femoral amputees to improve biomechanical function and reduce energy used in ambulation, although empirical data demonstrating an energy advantage of one particular design during walking remains scant. Moreover, research has yet to show that trans-femoral amputees can ambulate at an energy cost commensurate with levels reported for individuals without disability. For example, James (1973) reported that 37 trans-femoral amputees fitted with a quadrilateral (QUAD) socket consumed 40% more oxygen than non-disabled persons while ambulating at a pace that was 30% slower (51 m/mins=1.9 mph). Similarly, Traugh (1975) found that 9 trans-femoral amputee subjects fitted with QUAD sockets expended 65% more energy than non-disabled controls while walking at 39 m/min (1.45 mph), half the normal walking speed of the control subjects. Waters (1976) compared energy cost in vascular (n=13) and traumatic amputees (n=15) ambulating at a self-selected speed. The amount of energy consumed during ambulation was similar in both groups, although pace differed as subjects self-adjusted the walking speed to maintain minimal energy expenditure. Subjects with vascular amputation ambulated at 36 m/min (1.34 mph) while those with traumatic amputation walked at 52 m/min (1.94 mph), 56% and 37% slower respectively than non-disabled control subjects (82 m/min= 3.02 mph). Similarly, Huang *et al.* (1979) determined that trans-femoral amputees wearing a QUAD socket expended 49% more energy than able-bodied individuals while ambulating at 47 m/min (1.75 mph).

In an effort to improve biomechanical function and thus reduce metabolic cost of ambulation, John Sabolich designed the Contoured Adducted Trochanteric-Controlled Alignment Method (CAT-CAM) socket in the early 1980s. The CAT-CAM socket, more narrow in the mediolateral dimension than the QUAD socket, is designed to fit intimately with the ischial ramus, thus "locking" onto the pelvis, and encapsulating the ischial tuberosity. Additionally, the CAT-CAM socket has been claimed to improve muscular function, enhance pelvic motion, and maintain a more natural femoral adduction angle to a greater extent than the QUAD socket (Sabolich, 1985; Flandry *et al.*, 1989). Consequently, proponents of the CAT-CAM socket have suggested that this design is associated with a decreased energy requirement during ambulation by trans-femoral amputees. To date, however, there has been limited research which has shown a reduction in energy cost for those using the CAT-CAM socket. For example, Flandry *et al.* (1989) reported that five trans-femoral amputees fitted with both QUAD and CAT-CAM sockets used 56% less energy during ambulation with the latter. Ambulation speed of the CAT-CAM group was 44.5 m/min (1.66 mph), 16% faster than the pace of the subjects using the QUAD socket design (40.4 m/min= 1.5 mph), while sustaining reduced gait deviations and a slightly longer stride length. While this study suggests an energy and biomechanical advantage for the CAT-CAM socket during ambulation, the findings are compromised by the small study sample.

Therefore, the purpose of this study was to determine whether differences exist in energy expenditure during ambulation of trans-femoral amputees using QUAD and CAT-CAM sockets.

Methods

Subjects

Twenty unilateral trans-femoral amputees wearing either the CAT-CAM (n=10) or quadrilateral (QUAD) (n=10) socket and 10 non-amputee (control) subjects participated in this study. Subjects who met the following selection criteria were randomly selected: healthy males between the ages of 18 and 58 years (see results), amputation due to non-vascular pathology, unaffected sound limb, at least six months experience with the tested prosthesis, and a minimum stump length of 15 cm, measured from the greater trochanter to the distal lateral end of the femur, with the amputation site proximal to the femoral condyles. All subjects were free from any stump soft tissue problems, pain, or limitations that would influence their gait to an appreciable degree.

All amputee subjects were selected based upon the type of socket they were currently wearing. Subjects were not asked the name of their prosthetist, and as a result the investigators were not aware of the socket fabrication techniques employed by the prosthetists. Therefore, subjects were selected and tested purely of the basis of their socket design and not a single prosthetist's fabrication or casting technique.

Subjective criteria

The subjective criteria for the CAT-CAM socket were true ischial containment medially with no lateral gapping between the lateral wall and stump, an appropriate mediolateral and anteroposterior dimension for each individual amputee, and an appropriate femoral adduction angle. Criteria for the QUAD socket were: a posterior brim which an ischial seat, equal height of the medial and posterior brim, Scarpa's bulge anteriorly. Essentially, the socket design had to be consistent with the classic description of the quadrilateral socket by Radcliffe (1955). The same investigator evaluated every subject to provide standardisation in subject selection.

Procedure

Two trials were performed during which each subject ambulated at both 33.5 m/min (1.25 mph) and 67 m/min (2.5 mph). The order of trial was randomised and separated by a 20 minute rest period. Heart rate (HR) for each subject was measured using a Vantage

Performance Monitor.* Oxygen uptake (VO_2) was quantified by open-circuit spirometry using a calibrated Horizon System II Metabolic Measurements Analyzer** and Hans-Rudolph non-rebreathing valve. Non-exercise VO_2 and HR measurements were obtained during a one-minute of quiet standing before ambulation. Thereafter, each subject walked at one of the two designated speeds for eight minutes around a 36 metre, L-shaped, industrial carpeted indoor track. A metronome and verbal cues were used to pace subjects.

Data were collected during steady-state ambulation in the last three minutes of each trial.

Data analysis

Descriptive statistics (means and standard deviations) were generated for VO_2 and HR. A two-way ANOVA was peformed with time (pre-exercise, exercise) as the within subjects factor and ambulation pace (slow, fast) as the between subjects factor. In cases of significant F, post hoc testing was performed using Tukey and simple effects tests. In all cases, statistical significance was accepted at 0.05 level, or less.

Results

Descriptive characteristics of the study subjects (age, time after amputation, mass of prosthesis, stump length, time with present prosthesis) are shown in Tables 1 and 2. No significant age differences were found among the three study groups. The difference in mean time of socket wear prior to testing between the two groups (QUAD x=4.6 and CAT-CAM x = 1.6) is attributed to one QUAD subject who reported using his tested socket for the past 30 years. The mean time of socket wear prior to testing of the QUAD group exclusive of this one subject would be x=1.8 years. Eliminating this subject, there was no significant difference found in mean time of socket wear prior to testing between the two groups. The difference in mean age between the trans-femoral amputees did not differ from one another in any prosthetic or amputation-related characteristic studied as indentified in Table 2. All subjects were tested in their existing prosthetic componentry. Table 3 identifies the componentry worn by each subject.

*Polar Electro, Inc., USA P.O. Box 920, 300 Cottonwood Avenue, Hartland, WI 53029.
**SensorMedics Corporation, 1630 South State College Boulevard, Anaheim, CA 92806.

Table 1. Age mean and range.

Group	Age Mean	Age Range
CAT-CAM	37.2 ± 11.03	26–58
QUAD	34.6 ± 9.83	23–55
Control	33.2 ± 9.57	25–50

Means and standard deviations for pre-ambulation and ambulation VO_2 and HR are shown in Tables 4 and 5, respectively. No significant differences were observed for pre-ambulation VO_2 or HR, regardless of group or ambulation trial. At the slower pace, both QUAD and CAT-CAM groups showed higher VO_2 ($p<0.05$) and HR ($p<0.01$) than control subjects. No significant effect of socket type on VO_2 or HR was observed at slower pace. At the faster pace, however, VO_2 was significantly lower in subjects using the CAT-CAM socket that those using a QUAD socket ($p<0.01$). No effect on HR for the same groups under the same condition was observed.

Discussion

Two speeds of ambulation were chosen for this study because of the wide variance in walking velocity reported in the literature for trans-femoral amputees. Several authors have suggested that normal walking pace in persons with or without disability is approximately 82 m/min (3.0 mph) (Finley and Cody, 1970; Smidt, 1990; Fisher and Gullickson, 1978). However, it has been well-documented that trans-femoral amputees ambulate at slower speeds than normal, with a reported range of 36 to 52 m/min (James, 1973; Trough *et al.*, 1975; Huang *et al.*, 1979; Waters *et al.*, 1976; Flandry *et al.*, 1989; Fisher and Gullickson, 1978; Peizer *et al.*, 1969). To eliminate the effects of self-selected speeds on VO_2 and HR, two speeds were selected for study in this project (67 m/min

Table 2. Mean value comparison of prosthesis and residual limb.

	CAT-CAM	QUAD	t-values
Time after amputation	13.6 yrs	15.37 yrs	-0.51
Mass of prosthesis	3.64 kg	4.13 kg	-0.42
Residual limb length	0.63%	0.61%	0.27
Time with present prosthesis	1.61 yrs	4.6 yrs	-1.04

Table 3. Prosthetic componentry and mass of the limb worn by each subject.

CAT-CAM subjects	Knee unit	Foot assembly	Type of system	Mass of prosthesis kg
CC1	SA/Hyd	Seattle	Endoskeletal	3.54
CC2	4 Bar	Seattle	Exoskeletal	6.58
CC3	SA/Hyd	Seattle	Endoskeletal	3.18
CC4	SA/Hyd	Multi Flex	Endoskeletal	4.31
CC5	SA/Hyd	Multi Flex	Endoskeletal	3.41
CC6	SA/Hyd	Seattle	Endoskeletal	3.63
CC7	SA/Hyd	Multi Flex	Endoskeletal	2.81
CC8	SA/Pneu	Seattle Lite	Endoskeletal	2.77
CC9	SA/Hyd	Multi Flex	Endoskeletal	2.50
CC10	SA/Hyd	Multi Flex	Endoskeletal	3.54

Quad subjects	Knee unit	Foot assembly	Type of system	Mass of prosthesis kg
Q1	SA/Hyd	Seattle	Endoskeletal	2.77
Q2	SA/Pneu	Greissinger	Exoskeletal	4.45
Q3	SA/Hyd	SACH/Rot	Exoskeletal	7.26
Q4	SA/Hyd	Seattle	Exoskeletal	3.41
Q5	SA/Hyd	Seattle	Exoskeletal	3.63
Q6	SA/Hyd	Seattle/Rot	Exoskeletal	4.31
Q7	SA/Hyd	SACH	Exoskeletal	3.86
Q8	SA/Fric	SACH	Endoskeletal	4.54
Q9	SA/Hyd	Multi Flex	Endoskeletal	3.63
Q10	SA/Hyd	Multi Flex	Endoskeletal	3.41

SA=single axis 4 Bar=4 bar linkage system Hyd=hydraulic cadence control
Pneu=pneumatic cadence control Fric=friction control Rot=rotator

and 33.5 m/min). Smidt (1990) reported that "moderate" walking speed for persons without disability is betwen 60 an 79 m/min. Therefore, ambulation at 67 m/min in this study falls within the range of normal or moderate walking speed. The slower walking speed of 33.5 m/min represents 50% of this pace, and permits comparison of the two socket designs when amputees must ambulate at slow speeds because of high energy demand, challenging terrain and grade, or gait deviations.

The findings of this study support previous claims that the CAT-CAM socket reduces the metabolic cost of ambulation for trans-femoral amputees. Direct comparison of energy used while ambulating at normal walking speed (67 m/min=2.5 mph) showed subjects using the CAT-CAM design to require 20% less energy than those using the QUAD socket design. Moreover, indirect comparison of trans-femoral amputee subjects with normal controls showed energy consumption in the QUAD group to average 42% more than those without amputation at normal walking pace. In

Table 4. Means and standard deviations of non-exercise oxygen uptake and heart rate.

	Slow speed (33.5 m/min)		Fast speed (67 m/min)	
Group	VO_2	HR	VO_2	HR
CAT-CAM	5.4 ± 0.58	87.3 ± 10.96	5.53 ± 1.23	86.2 ± 11.63
QUAD	5.9 ± 1.30	85.4 ± 10.36	5.72 ± 1.88	87.5 ± 9.00
Control	4.9 ± 1.38	82.4 ± 7.26	5.12 ± 15.70	81.5 ± 11.05

Table 5. Means and standard deviations of oxygen uptake and heart rate.

	Slow speed (33.5 m/min)		Fast speed (67 m/min)	
Group	VO_2	HR	VO_2	HR
CAT-CAM	10.37 ± 1.34	101.42 ± 13.27	15.12 ± 1.89	116.42 ± 14.48
QUAD	11.72 ± 2.70	100.82 ± 10.61	18.98 ± 5.52	119.75 ± 16.28
Control	8.48 ± 1.08	83.86 ± 9.22	11.08 ± 1.88	90.04 ± 8.60

Table 6. Statistical significance and percentage difference between groups.

Group	Level of significance	Percentage
VO_2 comparison at 33.5 m/min		
Control vs CAT-CAM	significant at $p<0.01$	+18%
Control vs QUAD	significant at $p<0.01$	+28%
CAT-CAM vs QUAD	$p>0.05$ (non-significant)	+12%
VO_2 comparison at 67 m/min		
Control vs CAT-CAM	significant at $p<0.01$	+27%
Control vs QUAD	significant at $p<0.01$	+42%
CAT-CAM vs QUAD	significant at $p<0.01$	+20%
HR comparison at 33.5 m/min		
Control vs CAT-CAM	significant at $p<0.01$	+17%
Control vs QUAD	significant at $p<0.01$	+17%
CAT-CAM vs QUAD	$p>0.05$ (non-significant)	0%
HR comparison at 67 m/min		
Control vs CAT-CAM	significant at $p<0.01$	+23%
Control vs QUAD	significant at $p<0.01$	+25%
CAT-CAM vs QUAD	$p>0.05$ (non-significant)	+ 3%

contrast, subjects with CAT-CAM sockets used on 27% more energy at comparable walking speed.

While significant differences in VO_2 were observed while ambulating at 67 m/min, no significant effect of socket type on HR was observed at either walking speed. Others investigating the influences of socket design on metabolic responses to ambulation in trans-femoral amputees have either failed to report both VO_2 and HR data, or have observed significant differences in VO_2 without differences in HR (James, 1973; Waters *et al.*, 1976; Flandry *et al.*, 1989). While VO_2 and HR are known to rise in parallel during submaximal work, the disparate findings of the trans-femoral amputee subjects in this study with respect to VO_2 and HR responses to ambulation may be attributable to inter-individual differences in baseline levels of conditioning, or other unknown influence.

To date, the question as to why persons using the CAT-CAM socket use less energy during ambulation has yet to be meaningfully investigated, although proponents of this socket design suggest that: 1) by "locking" the medial wall to the ischial ramus, 2) containing the ischial tuberosity within the socket, and 3) maintaining the femur in an adducted position, energy may be conserved through optimisation of pelvic motion and gait mechanics. Additionally, the reduced energy cost of ambulation by trans-femoral amputees using a CAT-CAM design in the present study is consistent with previous speculation that this design places the stump musculature in a more optimal length-tension ratio than can be achieved when wearing a QUAD socket.

Conclusion

Direct comparison of energy cost during ambulation at normal speed showed that trans-femoral amputee users of a CAT-CAM socket design consumed less energy than amputees who used a QUAD socket. No energy advantage was observed for either socket design when subjects ambulated at slower pace. These findings have implications for optimal patient use of their prosthetic device and should assist prosthetists in selecting an appropriate socket design for their patients. Studies which compare the biomechanical characteristics of ambulation for these (and other) socket types and explain the observed energy advantage of the CAT-CAM socket are indicated.

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