

Physiological parameters analysis of transfemoral amputees with different prosthetic knees

SUJIAO LI^{1,2,3}, WUJING CAO^{1,2,3,4*}, HONGLIU YU^{1,2,3*},
QIAOLING MENG^{1,2,3}, WENMING CHEN^{1,2,3}

¹ Rehabilitation Engineering and Technology Institute, University of Shanghai for Science and Technology, Shanghai, China.

² Shanghai Engineering Research Center of Assistive Devices, Shanghai, China.

³ Key Laboratory of Neural-functional Information and Rehabilitation Engineering of the Ministry of Civil Affairs, Shanghai, China.

⁴ Guangdong Provincial Key Laboratory of Robotics and Intelligent System, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China.

Purpose: Physiological parameters analysis allows for a precise quantification of energy expenditure of transfemoral amputees with different prosthetic knees. Comparative physiological parameters analysis that indicate the functional characteristics of knee joints is essential to the choice of transfemoral amputee. The aim of this study was to propose a microprocessor-controlled prosthetic knee (i-KNEE) and conducted physiological parameters (energy cost, gait efficiency and relative exercise intensity) comparison of transfemoral amputees with C-leg, Rheo Knee and Mauch under different walking speeds. *Methods:* A microprocessor-controlled prosthetic knee with hydraulic damper (i-KNEE) was developed. A two-factor repeated measurement experiment design was used. Each subject was instructed to accept the same treatments. The two factors were type of prosthetic knees (the i-KNEE, the C-Leg, the Rheo Knee and the Mauch) and speed (0.5, 0.7, 0.9, 1.1, 1.3 m/s). The energy cost, gait efficiency and relative exercise intensity of ten transfemoral amputees were measured. *Results:* For all the prosthetic knees, the energy cost increased along with walking speed. There was no significant difference between three microprocessor-controlled prosthetic knees in energy cost. The gait efficiency of Mauch was always less than or equal to other three microprocessor-controlled prosthetic knees in specific walking speed. The relative exercise intensity increased with speed for all the prosthetic knees. More effort was needed for the transfemoral amputees with Mauch than other three microprocessor-controlled prosthetic knees in the same walking speed. *Conclusions:* The use of the microprocessor-controlled knee joints resulted in reduced energy cost, improved gait efficiency and smaller relative exercise intensity.

Key words: transfemoral amputee, microprocessor-controlled prosthetic knee, energy cost, gait efficiency, relative exercise intensity

1. Introduction

Transfemoral amputation means serious loss of lower-limb structures necessary to walk. Although a transfemoral prosthesis is usually installed to replace amputated or absent anatomical structures, notable difference of biomechanics and physiological parameters between transfemoral amputee and able-bodied person remain. The functional deficits of transfemoral prostheses often lead to decreased walking speed, reduced gait symmetry and increased energy cost and exercise intensity [10]. As

a result, transfemoral amputees are limited to participate in a narrow range of life activities.

A complete transfemoral prosthesis includes a prosthetic socket, knee, pylon and foot. The most important part of the transfemoral prosthesis is the prosthetic knee [7]. This is basically due to the fact that a prosthetic knee joint must provide stability in weight transfer during the stance phase, and enable the control of limb movement during the swing phase. The balance, frequency of stumbles and falls, activity level and ability in negotiating uneven terrain, hills, and stairs also depend on the performance of the prosthetic knee [1].

* Corresponding authors: Wujing Cao and Hongliu Yu, Rehabilitation Engineering and Technology Institute, University of Shanghai for Science and Technology, No.516, Jungong Road, Yangpu District, Shanghai, 200093, Shanghai, China. E-mail: caowujing414@126.com; yhl98@hotmail.com

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The prosthetic knee can be divided into three types: mechanically passive, microprocessor-controlled passive, and active prosthetic knee [3]. The mechanically passive knee cannot adapt to the change of walking speeds automatically [2]. Microprocessor-controlled passive knee interpret multiple source sensors to identify gait stages timely and microprocessor to adapt knee damping dynamically in changing gait [17]. Although it is still passive, the high performance has met the major needs of transfemoral amputee. Otto Bock Genium, C-leg and Össur Rheo Knee are typical commercial microprocessor-controlled passive knees. The active prosthetic knee can inject power into the knee and provide active torque [5]. However, the higher power and energy requirements of ambulation have limited commercial active prosthetic knees almost exclusively to energetically passive devices.

Microprocessor-controlled passive and active prosthetic knees feature unique combinations of sensors, dampers or actuators and control strategies. The intricate interaction of different factors directly affects biomechanical aspects of gait. These biomechanical factors may be related to the increased metabolic costs experienced by people with transfemoral amputations [6]. Physiological parameters analysis allows for a precise quantification of energy expenditure. These parameters represent the knee performance directly. At the same time, comparative physiological parameters analyses that indicate the functional characteristics of knee joints are essential to the choice of transfemoral amputee [12].

Several studies about performance difference of microprocessor-controlled prosthetic knees has been conducted. Highsmith et al. [11] researched whether the use of Genium improved functional performance compared to the C-Leg. The Continuous-Scale Physical Functional Performance-10 (CS-PFP10) assessment method was used, but it did not provide quantitative analysis. Hafner et al. [9] researched physical performance and self-report outcomes associated with use of passive, adaptive, and active prosthetic knees in persons with transfemoral amputation, they were also limited to self-reports and interviews. Thiele et al. [24] conducted a crossover design study. A small group of subjects was used to evaluate the performance of three microprocessor-controlled prosthetic knee joints (MPKs): C-Leg 4, Plié 3 and Rheo Knee 3, but they just conducted the biomechanical evaluation. Lura et al. [19] determined differences between the knee flexion angle of persons using the Genium knee, the C-Leg knee, and non-amputee controls, and evaluated the impact the prostheses had on gait and level of impairment of the user, it was also limited to kinematic analysis. In order to comprehensively and deeply un-

derstand the impact of different microprocessor-controlled prosthetic knee joints on transfemoral amputee, it is necessary to conduct physiological parameters analyses of transfemoral prostheses.

Physiological parameters commonly used include energy cost or oxygen consumption, gait efficiency, and relative exercise intensity [13]. The type of prosthetic knee is an important factor when considering ambulation for the person with transfemoral amputation, especially for persons with more active lifestyles. Prosthetic knee type influences on physiological parameters showed controversial results. Kaufman et al. [18] compared the energy expenditure using a mechanical and microprocessor-controlled prosthetic knee. The results demonstrated significantly increased physical activity-related energy expenditure levels in the participant's free-living environment after wearing the microprocessor-controlled prosthetic knee joint. There was no significant difference in the energy efficiency of walking. Jepson et al. [15] compared the Adaptive and Catech knee joints in established transfemoral amputees. There was no significant benefit gained from the use of the Adaptive knee over the Catech knee joint in their small study group. Orendurff et al. [20] conducted a prospective randomized crossover trial that compared the Mauch SNS knee and the C-Leg microprocessor-controlled knee in eight TF amputees. The C-Leg caused small reductions in net oxygen cost that were not statistically significant compared to the Mauch SNS at any of the walking speeds. These studies found no significant differences in energy cost between the microprocessor-controlled prosthetic knee and the mechanically passive knee. However, other studies comparing several different types of microprocessor-controlled prosthetic knees (the C-Leg, the Rheo Knee, and the IP) with the conventional mechanical passive knees have shown reduced energy cost and improved gait efficiency at different walking velocities. Johansson et al. [16] compared two variable-damping knees, the hydraulic-based Otto Bock C-leg and the magnetorheological-based Ossur Rheo, with the mechanically passive, hydraulic-based Mauch SNS. The results showed that when using the Rheo, metabolic rate decreases by 5% compared to the Mauch and by 3% compared to the C-leg. Wong et al. [26] examined studies comparing energy expenditure in users of non-MPK and MPK prostheses. A pattern of energy reduction with the use of a microprocessor, compared to non-MPK prostheses, emerged from the reviewed studies. The reduction in energy cost may be attributed to the simulated damping torque adjustment provided by the microprocessor-controlled prosthetic knees.

The purpose of this work was to propose a microprocessor-controlled prosthetic knee (i-KNEE) and conducted physiological parameters comparison to C-leg, Rheo Knee and mechanically passive, hydraulic-based Mauch. Firstly, the functional principle of the proposed microprocessor-controlled prosthetic knee was introduced. Secondly, the differences in energy cost, gait efficiency and relative exercise intensity of multiple-speed walking with different types of prosthetic knees were investigated and compared.

2. Materials and methods

Hydraulic prosthetic knee: damper, sensors and microprocessor

A microprocessor-controlled prosthetic knee with hydraulic damper (i-KNEE) was developed. The device, shown in Fig. 1, was self-contained with hydraulic damper, angle sensor, strain gage sensor, accelerometer, battery and electronic board.

The hydraulic damper had two separate microprocessor-controlled, motorized valves to generate knee joint resistance. Continuous adjustments of the hydraulic resistance for both movement directions could be re-

alized. A steel spring was used to store energy during flexion to support the subsequent extension. Two check valves were used to ensure the characteristics of one-way flow.

To control the resistive torque of the knee joint, the developed prosthetic knee used only mechanical sensing of knee position, force and torque. All sensors were positioned on the prosthetic knee or shank. Angle sensor measured knee flexion angle. The angle signal was differential to estimate knee angular velocity. Knee angle and velocity were critical for determining the gait velocity. Force strain gage sensor measured the force applied to the prosthetic knee from the ground. The ground reaction force was critical for identifying the gait phase. The accelerometer (9-axis inertial sensor) measured the gait posture of the lower limb. The acceleration signal could be used to establish the road condition and gait phase recognition algorithms. It was also useful for the security mode setting when the acceleration signal had sudden change.

Subjects

Ten subjects with unilateral transfemoral amputation were recruited to participate in the study. The study was approved by the local independent ethics com-

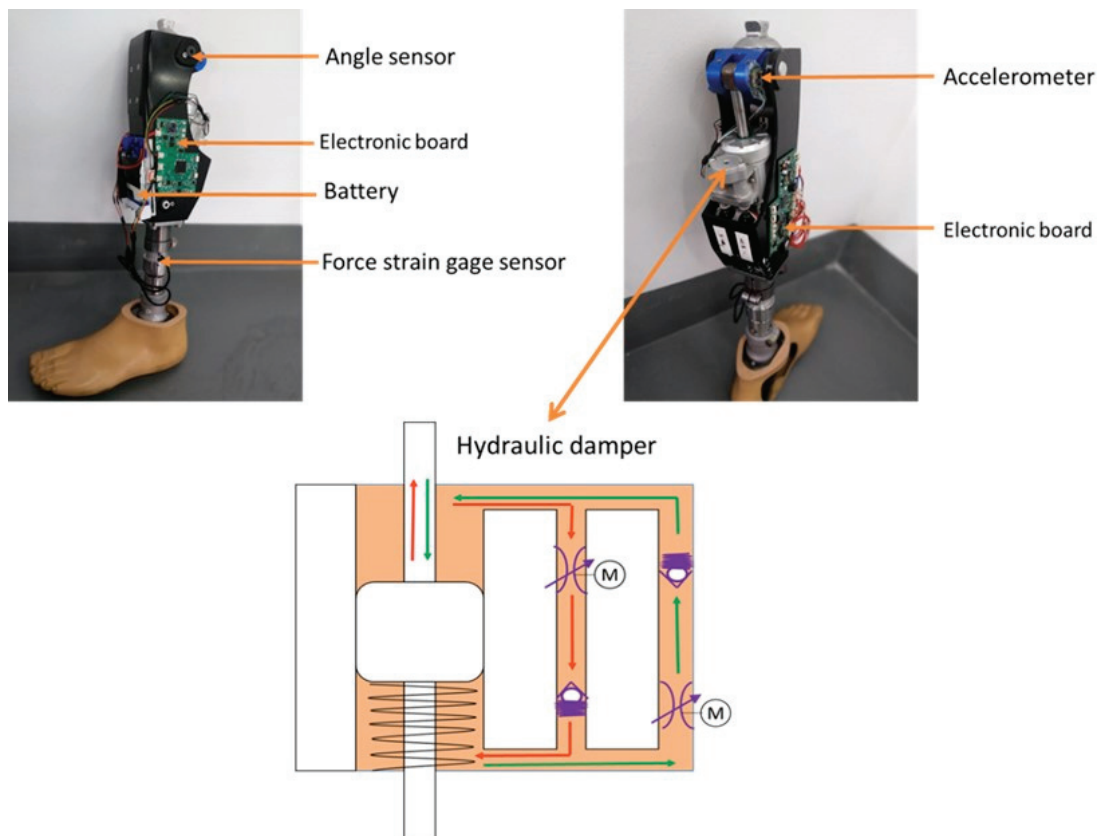


Fig. 1. The component of the proposed microprocessor-controlled prosthetic knee (i-KNEE)

mittee. Each subject gave their written informed consent before testing. The participants (seven male, three female) were 20–45 years old, 158–178 cm in height, and weighed 50–78 kg. Patient characteristics are summarized in Table 1.

Table 1. Subject demographics

Subject	Gender	Age [years]	Weight [kg]	Height [cm]	Prosthetic use [years]	Amputation cause
1	F	20	50	158	3	Accident
2	M	26	70	173	8	Accident
3	M	23	65	175	1	Accident
4	M	35	70	172	8	Accident
5	F	38	55	160	3	Disease
6	M	45	78	178	15	Accident
7	M	33	75	176	2	Disease
8	M	44	67	173	3	Disease
9	F	21	58	163	1	Accident
10	M	32	66	175	2	Accident

The clinical examination were also conducted before they were included in the research. They had no osteoarticular, muscular, or neurologic disease that could affect their gait. They were all capable to understand the study protocol completely. The mobility grade of Medicare Functional Classification Level of all the transfemoral amputees were from K3 or higher. The Triton (Ottobock) prosthetic foot was provided for all prosthetic knee conditions. The socket kept to be same across the trials. The same experienced prosthetist had also successfully completed special training in the application of the microprocessor knee, performed all alignment and fitting trials. Prosthetic alignment was confirmed with an L.A.S.A.R. posture system.

Experimental design and general procedures

A two-factor repeated measurement experiment design was used. Each subject was instructed to accept the same treatments. The two factors were type of prosthetic knees (the i-KNEE, the C-Leg, the Rheo Knee and the Mauch) and speed (0.5, 0.7, 0.9, 1.1, 1.3 m/s). The test prosthetic knee was worn for at least 3 days

before the experiment to enable acclimatisation. Subjects were familiarized with treadmill walking prior to determination of their oxygen consumption and heart rate. All subjects completed the walking tasks with progressive incremental ambulation. Testing consisted of ambulating on the treadmill for 6 min in each speed. After a 10-min rest, the subject completed the same procedure with the next speed. Subjects who found the treadmill speed too fast were able to stop at an intermediate speed. Testing order was randomly assigned across the subjects.

The dependent variables included energy cost, gait efficiency, and relative exercise intensity. Energy cost and heart rate were quantified through direct measurement. The exercise cardiopulmonary testing system MasterScreen CPX (Jaeger, Viasys Healthcare, Hoechst, Germany) was used. This system guarantees outstanding “Breath-By-Breath” performance features and ease of operation. The system modules were able to record energy cost and heart rate simultaneously. The criterion for gait efficiency was chosen to be energy cost per meter traveled ($\text{mL O}_2/\text{kg}/\text{m}$). The percentage of age-predicted maximum heart rate (%APMHR), expressed using the formula ($\text{exercise heart rate}/\text{age-predicted maximum heart rate} \times 100$), set as the index of relative exercise intensity.

Statistical analysis

Statistical analysis was performed using a commercial statistical analysis package (SAS 9.4, Cary, NC, USA). A two-way repeated analysis of variance (ANOVA) was used to test for main effects and interaction of knee type (the i-KNEE, the C-Leg, the Rheo Knee and the Mauch) versus speed of ambulation. Means and standard deviations were calculated for each variable. The probability level of $P < 0.05$ was used to determine the statistical significance.

3. Results

The energy cost, gait efficiency and relative exercise intensity were analyzed under different walking

Table 2. Analysis of variance summary for walking tests

Variable	df	Energy cost		Gait efficiency		Relative exercise intensity	
		F	P	F	P	F	P
Knee	3	0.47	0.7060	0.33	0.8005	1.32	0.2802
Speed	4	37.21	5.55E-13	29.45	1.90E-11	7.92	8.42E-5
Knee by speed	12	0.06	0.9994	0.08	0.9997	0.01	1

speeds in ten subjects with transfemoral amputations with the i-KNEE, the C-Leg, the RheoKnee and the Mauch. The ANOVA summary for walking tests is shown in Table 2. For energy cost, gait efficiency and relative exercise intensity, the main effect F statistics for differences of knee type were not significant, while the walking speed was significant. The ANOVA also indicated that the knee type by speed interaction was nonsignificant. The P -values also demonstrated that there was no significant difference for the effect of knee type. There was significant difference for all the physiological parameters of the effect of speed.

Energy cost

The energy cost data of the subjects were numerically (means and standard deviations) showed in Table 3. For all the prosthetic knees, the energy cost increased with walking speed. In all speeds, the energy cost of the mechanical passive knee Mauch was higher than other three microprocessor-controlled prosthetic knees. There was no significant difference between three microprocessor-controlled prosthetic knees in each speed. The energy cost of i-KNEE was lower than the C-Leg and the RheoKnee in 0.7, 0.9, 1.1 and 1.3 m/s. However, the energy cost of the RheoKnee was the lowest in 0.5 m/s. The energy cost of the RheoKnee was smaller than the C-Leg in all the speeds.

Gait efficiency

The gait efficiency data of the subjects were numerically (means and standard deviations) showed in Table 4. The numerical value decreased with the higher

speed for all the prosthetic knees from 0.5 to 0.9 m/s. For the gait efficiency, the lower the numerical value, the more efficient the gait. It means the gait efficiency increased with the higher speed for all the prosthetic knees from 0.5 to 0.9 m/s. The gait efficiency also increased with higher speed for the i-KNEE, the C-Leg and the RheoKnee from 1.1 to 1.3 m/s. However, the higher numerical values were obtained for i-KNEE and RheoKnee from 0.9 to 1.1 m/s. The numerical values kept the same for C-Leg from 0.9 to 1.1 m/s. The numerical values of mechanical passive knee Mauch were greater than or equal to other three microprocessor-controlled prosthetic knees in each speed. It means the gait efficiency of Mauch were always less than or equal to other three microprocessor-controlled prosthetic knees in specific walking speed. However, there was no significant difference for gait efficiency between the i-KNEE, the C-Leg, the RheoKnee and the Mauch in all the specific walking speed.

Relative exercise intensity

The relative exercise intensity data of the subjects were numerically (means and standard deviations) showed in Table 5. The %APMHR increased with speed for all the prosthetic knees. The numerical values of mechanical passive knee Mauch were bigger than other three microprocessor-controlled prosthetic knees at all specific walking speeds. It means more effort was needed for the transfemoral amputees with Mauch than other three microprocessor-controlled prosthetic knees at the same walking speed. For the three microprocessor-controlled prosthetic knees, the numerical

Table 3. Mean energy cost (mL O₂/kg/min) for the ten subjects with transfemoral amputation for the walking tests

Speed [m/s]	Mean (SD)			
	i-KNEE	C-Leg	RheoKnee	Mauch
0.5	12.46 (1.35)	12.35 (1.27)	12.24 (1.42)	12.52 (1.32)
0.7	13.55 (1.62)	14.02 (1.58)	13.65 (1.74)	14.12 (1.68)
0.9	14.52 (1.98)	14.86 (1.84)	14.74 (1.92)	15.25 (2.05)
1.1	18.36 (2.04)	18.75 (1.95)	18.52 (2.10)	19.25 (2.58)
1.3	20.55 (2.85)	20.85 (2.55)	20.72 (2.65)	22.35 (3.25)

Table 4. Mean gait efficiency (mL O₂/kg/m) for the ten subjects with transfemoral amputation for the walking tests

Speed [m/s]	Mean (SD)			
	i-KNEE	C-Leg	RheoKnee	Mauch
0.5	0.42 (0.05)	0.41 (0.04)	0.41 (0.05)	0.42 (0.04)
0.7	0.32 (0.04)	0.33 (0.04)	0.33 (0.04)	0.34 (0.04)
0.9	0.27 (0.04)	0.28 (0.03)	0.27 (0.04)	0.28 (0.04)
1.1	0.29 (0.03)	0.28 (0.03)	0.28 (0.03)	0.29 (0.04)
1.3	0.26 (0.04)	0.27 (0.03)	0.27 (0.03)	0.29 (0.04)

Table 5. Mean %APMHR for the ten subjects with transfemoral amputation for the walking tests

Speed [m/s]	Mean (SD)			
	i-KNEE	C-Leg	RheoKnee	Mauch
0.5	44.35 (3.85)	43.26 (3.15)	42.95 (3.87)	46.58 (5.16)
0.7	46.56 (4.23)	44.85 (3.25)	44.52 (4.35)	48.68 (6.27)
0.9	49.36 (4.78)	48.94 (3.98)	47.54 (5.23)	51.65 (7.25)
1.1	52.35 (5.95)	51.82 (5.24)	50.73 (6.05)	54.86 (8.52)
1.3	56.75 (7.38)	55.37 (6.96)	54.13 (7.25)	58.35 (9.54)

values of RheoKnee were smaller than i-KNEE and C-Leg at each walking speed. However, there was no significant difference for the relative exercise intensity between the three microprocessor-controlled prosthetic knees in the specific walking speed.

4. Discussion

This study was designed to propose a microprocessor-controlled prosthetic knee and conducted physiological parameters comparison with C-leg, Rheo Knee and mechanically passive, hydraulic-based Mauch. A microprocessor-controlled prosthetic knee with hydraulic damper and multi-sensors was designed. The energy cost, gait efficiency and relative exercise intensity were chosen as the physiological parameters to quantitative analysis the performance difference of different prosthetic knees. The study demonstrated that transfemoral amputees decreased their energy cost and relative exercise intensity when using microprocessor-controlled prosthetic knees in the same walking speed. However, the gait efficiency showed mixing results. There was no significant improvement for gait efficiency.

Recently, engineers have begun to speculate whether active knee torque loss may be a factor limiting the walking performance of microprocessor-controlled prosthetic knees. Some microprocessor-controlled prosthetic knees with active or active-passive hybrid torque mechanism has been researched. Geeroms et al. [8] developed and tested a novel semi-active actuator with a lockable parallel spring for a prosthetic knee joint. The results showed that the proposed novel actuator reduced the energy consumption for the same trajectory with respect to a compliant or directly-driven prosthetic active knee joint and improved the approximation of healthy knee behavior during level walking compared to passive or variable damping knee prostheses. Park et al. [22] proposed a new prosthesis operated in two different modes: the semi-active and active ones. The semi-active mode was achieved from

a flow mode magneto-rheological (MR) damper, while the active mode was obtained from an electronically commutated (EC) motor. It was demonstrated that the desired knee joint angle was well achieved in different walking velocities on the level ground. Ahn HJ et al. [14] described the optimized design of a knee joint for an active transfemoral prosthesis with a fully active knee joint. The prosthetic knee joint had a high-torque mechanism comprising a flat BLDC motor, harmonic drive, and pulley to generate the torque required for walking on stairs, which required the largest torque. It is therefore attractive to speculate that active-passive hybrid control mechanism could improve walking ability by minimizing the normal torque. Future studies should consider combination of actuators and dampers to further clarify potential clinical implications.

Energy cost was higher in people with transfemoral amputation because of deviations in gait pattern and gait symmetry, and increased involvement of the upper body, particularly in terms of lifting the affected side pelvis resulting in increased lifting of the centre of motion. The results in this work demonstrated that better biomechanical parameters may have been obtained in microprocessor-controlled prosthetic knees than mechanical passive knee indirectly. However, the energy cost between microprocessor-controlled prosthetic knees was not significant. Previous investigations using C-Leg and RheoKnee in comparison with Mauch showed reductions in metabolic cost, similar to that observed in this work [16]. However, the microprocessor-controlled prosthetic knees used in this work were passive. The energy cost difference in microprocessor-controlled active and passive knees may be significant. Williams et al. [25] tested an original variable-impedance transmission prosthetic knee (microprocessor-controlled active) in five study participants with unilateral transfemoral amputation at two steady state walking speeds, one below and one above their preferred walking speed. While walking with the variable-impedance knee, participants with shorter limbs showed a reduction in metabolic cost, compared to their C-Leg prosthesis, while those with longer

limbs exhibited an increase in this parameter. Martinez et al. [20] compared the antagonistic active knee prosthesis developed at MIT to an electronically controlled, variable-damping commercial knee prosthesis, the Otto Bock C-leg. Use of the active knee prosthesis resulted in a 6.8% reduction in metabolic cost.

The criterion for gait efficiency was chosen to be energy cost per meter traveled ($\text{mL O}_2/\text{kg/m}$). This parameter was most often employed to describe gait as a function of speed and to assess prostheses aiming to reduce energy expenditure or to achieve energy expenditure close to that of able-bodied subjects. Chin et al. [4] researched gait efficiency for the subjects using the IP and C-Leg and the able-bodied group at specific walking speed. The gait efficiency was used to determine the most efficient speed from energy terms. The results showed that the most energy-efficient walking speed for subjects using the IP and C-Leg was the same as for able-bodied persons.

Although energy cost, gait efficiency and relative exercise intensity were commonly used physiological parameters, there were other physiological parameters found in previous studies. For example, the EMG intensity and duration were employed to describe and quantify stump muscle activity. Silver et al. [23] assessed the feasibility of using myoelectric control of future active or powered prosthetic ankle joints for trans-tibial amputees. The result indicated that trans-tibial amputees retained some independent ankle plantarflexor and dorsiflexor muscle activity of their residual limb.

This study had several limitations. First, the diet during testing the prosthetic knees was not controlled. The physiological parameters may be affected by drinking alcohol. Second, the test was only conducted on treadmill to simulate level walking. The test for different prosthetic knees in real ambulation environment should be researched.

5. Conclusions

The functional principle of the proposed microprocessor-controlled prosthetic knee with hydraulic damper was introduced in this work. The results of this study indicated. There was no significant difference between three microprocessor-controlled prosthetic knees in energy cost. The gait efficiency of Mauch were always less than or equal to other three microprocessor-controlled prosthetic knees in specific walking speed. More effort was needed for the transfemoral amputees with Mauch than other three microprocessor-controlled

prosthetic knees in the same walking speed. Use of the microprocessor-controlled knee joints resulted in reduced energy cost, improved gait efficiency and smaller relative exercise intensity.

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