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Plantar pressure analysis of above-knee amputee with a developed microprocessor-controlled prosthetic knee

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Purpose: Human gait motion analysis was one useful method for lower limb prosthesis study. The most often measured parameters were plantar pressure, kinetic and kinematic parameters. It was indispensable for prosthetic knee design and performance assessment. The aim of this study was to analysis the plantar pressure in traumatic above-knee amputee equipped with a developed microprocessor-controlled prosthetic knee. *Methods:* The maximum force of forefoot and rearfoot, the average vertical reaction force and pressure and the centre of pressure (COP) offset trajectories of ten above-knee amputees under different walking speeds were obtained. *Results:* Both forefoot and rearfoot force were bigger in intact leg than prosthetic leg. As the speed increased, the pressure increased in both sides. Forefoot bore more pressure than rearfoot in both legs. The average vertical pressure and force both increased along with the increase of speed. The force and pressure of intact side were always bigger than the prosthetic side. The trend of COP and gait line of the prosthetic and intact side had no significant difference. The length of the gait line of prosthetic side was greater than the intact side. *Conclusions:* The results of this study exhibited reduced plantar pressure in the prosthetic side. The typical butterfly diagrams were produced during different walking speeds. It indicated that the stability of the microprocessor-controlled prosthetic knee could be guaranteed.

Key words: *plantar pressure, above-knee amputee, microprocessor-controlled, prosthetic knee, gait analysis*

1. Introduction

There are more than 800,000 above-knee amputees in China, with 60,000 new above-knee amputations conducted each year [18]. The above-knee amputee is commonly a result of problems with the blood vessels in the leg. Other causes of limb loss mainly include severe injuries of accidents, treatment of cancer, infections and complications of muscle and bone illness [13]. To recover walking ability, amputees have to install artificial leg. An artificial leg for a person with above-knee amputation generally consists of a socket, a knee joint, a pylon, and a prosthetic foot. The knee joint largely determines the amputee's ability to ambulate safely and efficiently with the artificial leg. It has a considerable influence on the mobility level the amputee will reach.

Much effort and engineering expertise have been invested in the design of various knee units. Prosthetic knees can be classified into three categories: passive, microprocessor-controlled and powered [6]. Passive prosthetic knees are purely mechanical devices with some form of damper and have no source of power. By incorporating microcontrollers, microprocessor-controlled prosthetic knees are able to vary the damping or resistance of the prosthetic knees during the gait cycle to provide more efficient ambulation compared to the passive prosthetic knees. Powered prosthetic knees are composed of miniaturized motors or hydraulic actuators to provide the required positive energy during ambulation. Powered prosthetic knees

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have limited application because of their large power consumption compared to microprocessor-controlled prosthetic knees. Prostheses design deserves precise, objective, functional assessment, which can be provided by kinematic and kinetic gait analysis. The information obtained from gait analysis can also guide future designs of prosthetic knee components.

Gait patterns of above-knee amputees differ from normal gait. Measures of gait mechanics reported in the prosthetic knee literature include walking speed, spatial step symmetry, temporal step symmetry, kinematics, joint moment, joint power and ground reaction force (GRF) [25]. Prinsen et al. compared the Rheo Knee II (a microprocessor-controlled prosthetic knee) to passive prosthetic knees at varying walking speeds. No differences on peak prosthetic knee flexion during swing were found between prosthetic knee conditions. In addition, prosthetic knee flexion increased significantly with walking speed for both prosthetic knee conditions [17]. Lura et al. determined differences between the knee flexion angle of persons using the Genium knee, the C-Leg knee, and non-amputee controls. The results indicated that Genium knee generally increased flexion in swing and stance, potentially decreased the level of impairment for persons with transfemoral amputation [14]. The authors of [14] also researched the relative efficacy of the Genium and C-Leg prostheses for stair ascent and descent, and their absolute efficacy relative to non-amputees. An eight camera Vicon optical motion analysis system, and two AMTI force plates were used to track and analyse the participants' gait patterns, knee flexion angles, knee moment normalized by body weight, and swing time [15]. Hafner et al. studied physical performance and self-report outcomes associated with use of passive, adaptive, and active prosthetic knees in persons with unilateral, trans-femoral amputation. Findings suggested that adaptive knee control may enhance function, compared to passive control, but that active control can restrict mobility in middle-age or older users with transfemoral amputation [10]. Jaroslav et al. compared angle parameters in knee and hip joints during the gait of transfemoral amputees and determined the effect of the type of knee joint used on their symmetry. Flexion at heel contact and maximum swing flexion in the knee joint were more symmetrical in the group with hydraulic knee joints; for all other parameters the group with bionic knee joints achieved better symmetry [12]. Previous work of authors had proposed a new microprocessor-controlled prosthetic knee and compared it with passive prosthetic knees [3], [26]. The focus of previous work were comparison of comfortable self-selected walking speed, maximum swing flexion knee angle and gait symmetry between the microprocessor-controlled and passive prosthetic knees under different walking speeds. The main biomechanical parameters researched of above-knee amputees were walking speed, knee angles and gait symmetry.

Plantar pressure analysis often researched on transtibial amputee subjects. Tominaga et al. verified the effects of sagittal plane alignment changes in running-specific transtibial prostheses on ground reaction forces [23]. Raja et al. compared the effect of vertical ground reaction force on unilateral transtibial amputees using conventional and modular patellar tendon bearing prosthesis with stump exercises [19]. Sharifmoradi et al. analyzed the components of ground reaction forces in healthy leg and prosthetic leg in the patients with unilateral below-the-knee amputation [22]. Few research of plantar pressure analysis has been conducted to above-knee amputees.

The aim of this study was to analyses the plantar pressure in traumatic above-knee amputee equipped with a developed microprocessor-controlled prosthetic knee. Firstly, we introduced the developed microprocessor-controlled prosthetic knee with hydraulic damper. Secondly, we hypothesized that the maximum force of forefoot and rearfoot would be bigger in the intact side. In addition, we hypothesized that the average vertical reaction force and pressure would be increased along with the walking speed increase. Finally, we compared the centre of pressure (COP) offset trajectories under different walking speeds. We hypothesized that the patient would have better symmetry between prosthetic and intact side when wearing the developed microprocessor-controlled prosthetic knee.

2. Materials and methods

Technical background of developed microprocessor-controlled prosthetic knee

The microprocessor-controlled prosthetic knee used a hydraulic cylinder to provide not only superior swing phase responsiveness but also variable hydraulic stance phase control (Fig. 1). The proposed hydraulic system (Fig. 1B) had two separate needle valves (2a, 2b) to generate joint resistance for the flexion and the extension movement. The valves opening was controlled by linear motors. With the change of valve opening, the flow resistance could be continuously varied from low to high values. When the piston 1 moved down during flexion, the oil flowed through flexion

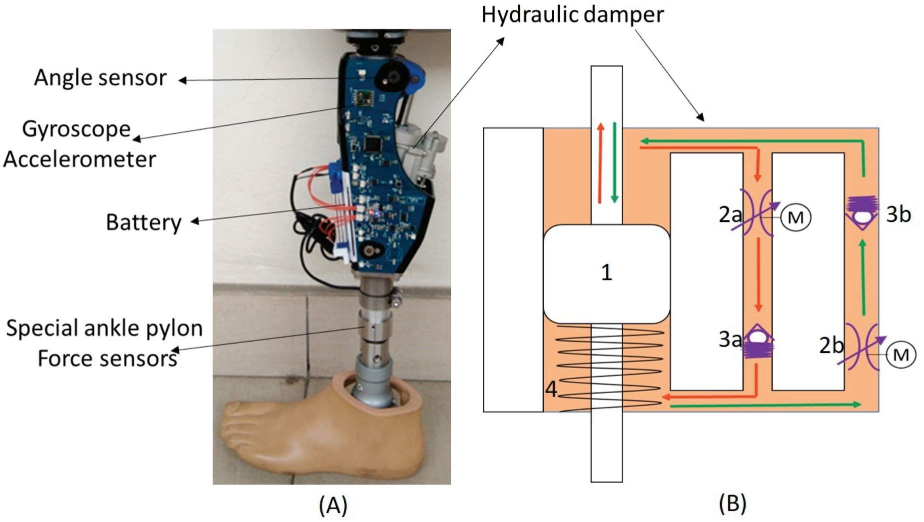

Fig. 1. (A) Microprocessor-controlled prosthetic knee, (B) Hydraulic system

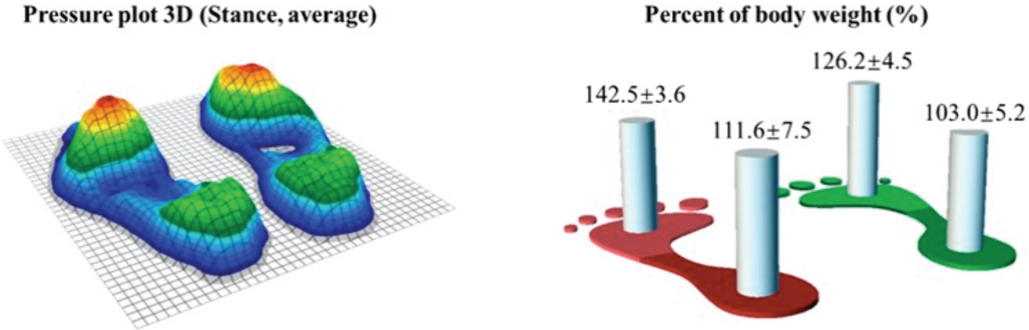

Fig. 2. Maximum force for fore and rear foot of above-knee amputees at 0.5m/s

needle valve 2b and check valve 3b (flow marked in green). The steel spring was pressed during flexion by the displacement of the piston rod. For extension, the piston moved up and the oil passed extension needle valve 2a and check valve 3a (flow marked in red). The energy stored by compression of steel spring 4 was released. This could provide assistance for extension. This design also used multiple sensors (Fig. 1A) that were integrated into the prosthetic shin structure to gather and calculate biomechanical data, such as the amount of vertical loading, and the position, direction, and angular acceleration of the knee joint. These data were sampled to allow the computer to adjust the knee accordingly [4].

Subjects

Ten males with right trans-femoral amputation volunteered for the investigation. The above-knee amputees were recruited from Shanghai Artificial Limb Factory, a large disability rehabilitation center in China. They wore prosthetic knee for approximately 10 hours a day. The amputee subjects met the following criteria: a) amputation were performed at least 2 years ago; b) amputation were caused by trauma; c) the subjects were optimally fitted with a microprocessor-controlled prosthetic knee; d) the subjects showed no major gait deviations; e) the subjects were able to walk without a walking stick or other support. All the subjects did not suffer from further limitations of the vascular diseases. Subject demographics are described in Table 1. Before the study was conducted, the authors obtained an informed consent. Because the protocol of our study was completely non-invasive and painless, no ethical approval was required. Moreover, gait analysis was added to the usual clinical evaluation only if both the amputee and his doctor agreed. The protocol was performed with a medical doctor and a prosthetist.

Experimental procedure

The same certified prosthetist fit the prosthesis in the study. He optimized the alignment for maximal function using standard subjective, trial and error techniques. Objective documentation and adjustment of prosthetic alignment was conducted using

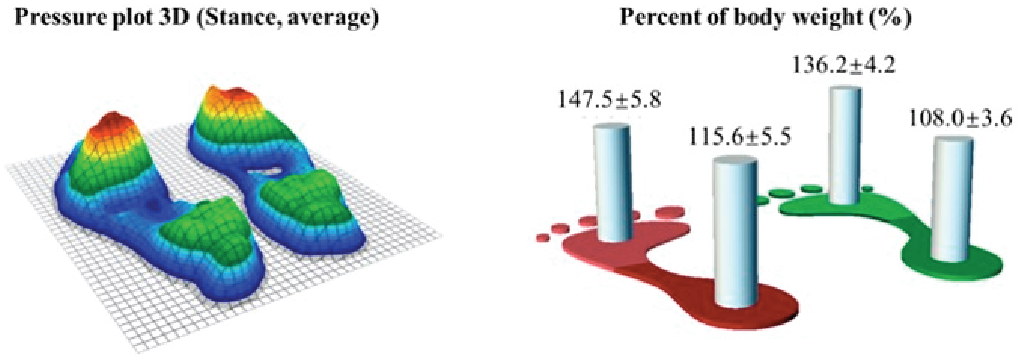

Fig. 3. Maximum force for fore- and rearfoot of above-knee amputees in 0.8 m/s

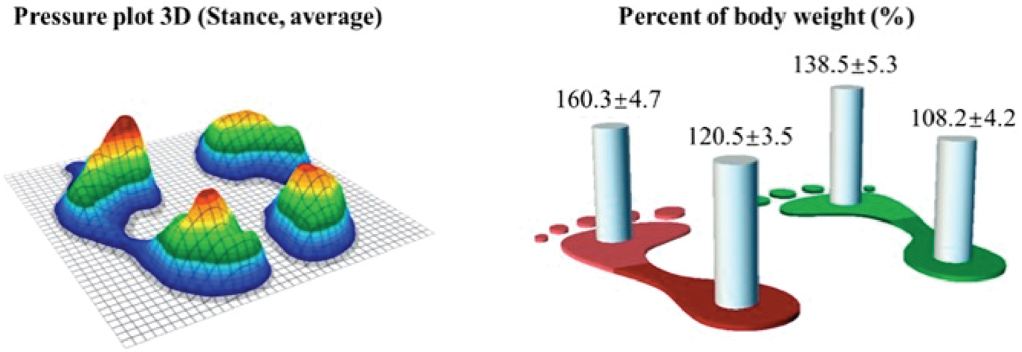

Fig. 4. Maximum force for fore- and rearfoot of above-knee amputees in 1.1 m/s

the LASAR-POSTURE device (Otto Bock, Germany). A description of this device and its application for lower limb patients can be found in Ref. [21]. The prosthetic foot of the amputees were Triton 1C60 (Otto Bock, Germany). At the beginning of this study, the amputees had been using the developed microprocessor-controlled prosthetic knee three months.

The measurements were performed in a motion analysis laboratory of Shanghai Engineering Research Center of Assistive devices. Plantar pressure was measured using zebris FDM system (zebris Medical Gmbh, German) which was accurate and user-friendly for pressure analysis. Zebris FDM system was a treadmill system with 5300 built-in pre-calibrated capacitive sensors for the analysis of force and pressure distribution during standing, walking and running, which could be completed in less than 30 seconds [9].

The above-knee amputees performed three test series on the treadmill of zebris FDM system to simulate level walking. Each test series consisted of ten repetitions at three specific velocities: slow (0.5 m/s), medium (0.8 m/s) and fast (1.1 m/s). An average of at least two minutes walking trial was collected to gather the mean walking parameters. Every gait cycle per trial was recorded within the zebris FDM system. By using the zebris FDM system, the gait data were continuously recorded. The step recognition was fully automatic, and all steps with complete measuring data were included. Kinetic data were obtained with the aid of zebris FDM system, which provided measurement of average maximum pressure, average vertical reaction force and three foot zone analysis.

The comparisons of maximum force of forefoot and rearfoot, average vertical reaction force and pressure and center of pressure (COP) offset trajectories were performed. The parameters were researched under three specific walking speeds.

Table 1. Subject demographics

Subject	Age [years]	Height [cm]	Weight [kg]	Gender
1	36	173	65	Male
2	43	174	68	Male
3	40	172	63	Male
4	38	173	65	Male
5	42	175	70	Male
6	41	172	65	Male
7	37	173	64	Male
8	32	172	67	Male
9	40	173	65	Male
10	34	174	70	Male

3. Results

Maximum force of fore foot and rear foot

Plantar pressure were signal presented as a percent of body weight (BW) to eliminate effects of different body weight. Maximum force of forefoot and rearfoot results for prosthetic legs and contra-lateral legs of amputees in different walking speeds were shown in Figs. 2–4.

Both forefoot and rearfoot force were bigger in intact leg than prosthetic leg. The pressure increased in both sides with the speed increase. Fore foot bore more pressure than the rear foot in both legs.

Average vertical reaction force and pressure

The average vertical reaction force and pressure of a typical above-knee amputee under different walking speeds were chosen to be shown in Figs. 5–7. The standard deviation was shown as a shaded area, the dotted line represented intact leg. Solid line represented the prosthetic leg. The vertical line separated the stance and swing phase.

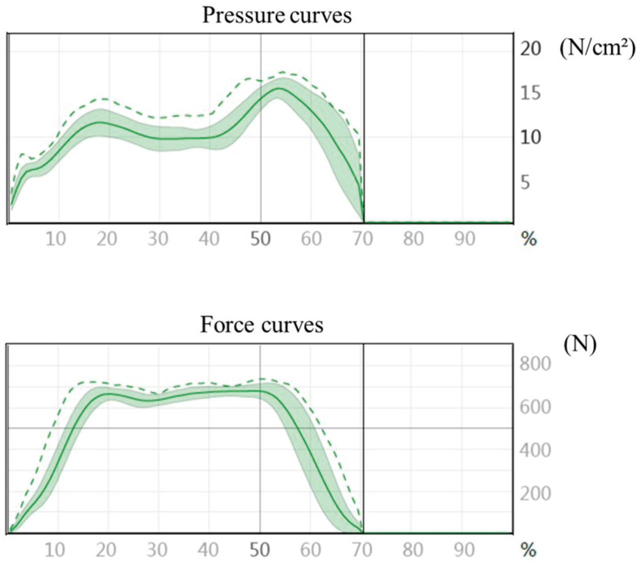

Fig. 5. The average vertical reaction force and pressure curves at 0.5 m/s

Both the average vertical pressure and force increased with the speed increase. The intact side force and pressure were always bigger than the prosthetic side. The percent of stance phase would be smaller when the speed increase.

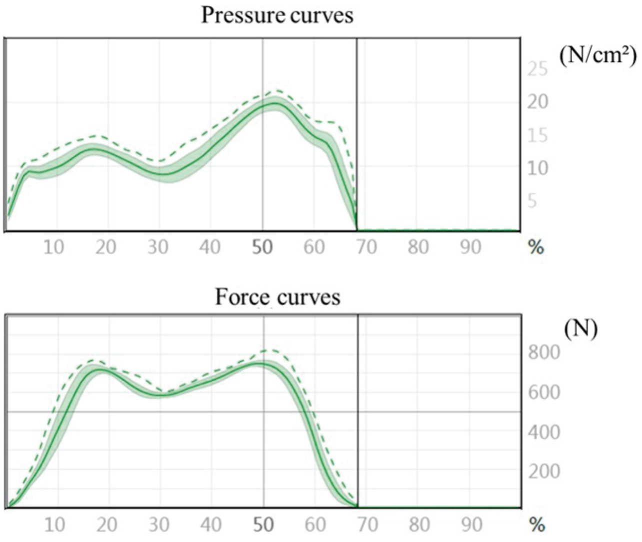

Fig. 6. The average vertical reaction force and pressure curves at 0.8 m/s

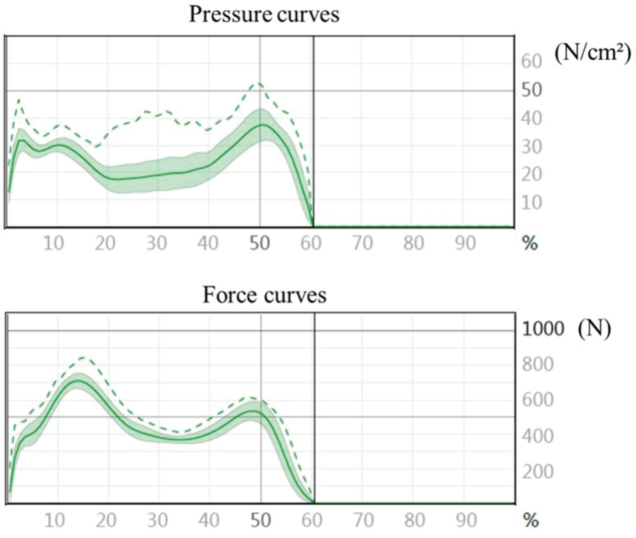

Fig. 7. The average vertical reaction force and pressure curves at 1.1 m/s

Centre of pressure (COP) offset trajectory at different speeds

The centre of pressure (COP) offset trajectories of a typical above-knee amputee under different walking speeds were chosen to be shown in Fig. 8.

The COP moved from the rearfoot to the forefoot of the same side. Then it moved to the other side of the rearfoot and the forefoot. The trend of COP and gait line of the prosthetic and intact side had no significant difference. The length of the gait line of prosthetic side was greater than the intact side. The typical butterfly diagrams were produced during different walking speeds. It indicated that the stability of the microprocessor-controlled prosthetic knee could be guaranteed.

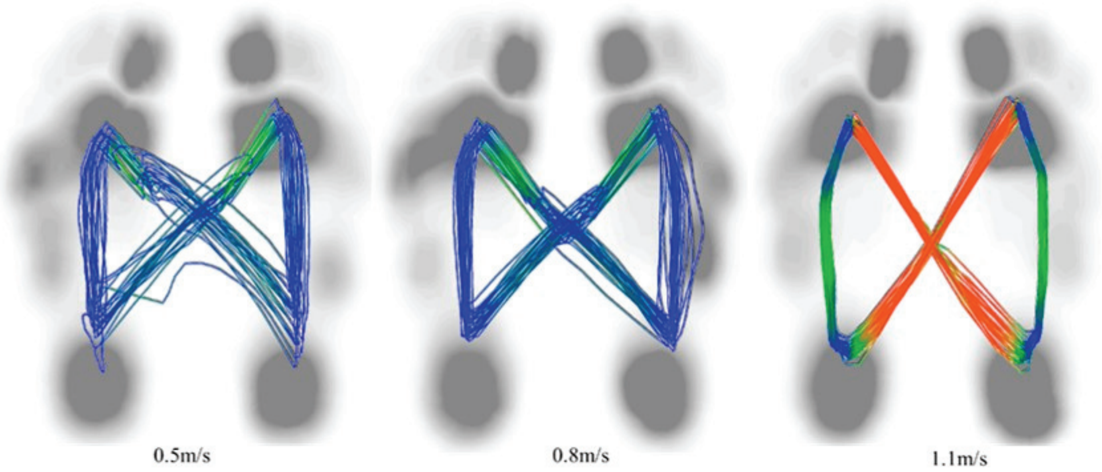

Fig. 8. Centre of pressure (COP) at different speeds

4. Discussion

The first goal of this study was to propose a novel microprocessor-controlled prosthetic knee. Although the developed microprocessor-controlled prosthetic knee utilizing hydraulic damper offered several advantages, it lacked the ability to generate active force that was required during some states of a normal gait cycle. The developed damping knee prostheses may cause an asymmetric gait and higher metabolic cost, compared to non-amputees. Geeroms et al. proposed a novel semi-active actuator with a lockable parallel spring for a prosthetic knee joint. The novel actuator improved the knee behavior, compared to passive or variable damping knee prostheses, and reduced the energy consumption with respect to a compliant or directly-driven prosthetic active knee joint [8]. Ekkachai et al. proposed a new control algorithm for a semi-active prosthetic knee during the swing phase. The neural network predictive control and particle swarm optimization were used to calculate suitable command signals. The investigation showed that the algorithm could be calculated in real time allowing for easy implementation on real prosthetic knee [7]. Abdelhady et al. mounted DC motor to a Mauch SNS prosthetic knee to obtain an active prosthetic knee. The particle swarm optimization (PSO), sequential quadratic programming (SQP) and biogeography-based optimization (BBO) were compared for system identification [1]. Park et al. proposed a prosthetic knee operated in semi-active and active modes. The semi-active mode was achieved through a magneto-rheological (MR) damper. The active mode was obtained from an electronically commutated (EC) motor. Results showed that the desired knee joint angle could be achieved in different walking velocities during level walking [16]. Awad et al. presented a back-drivable semi-active prosthetic knee. The mathematical model and analysis of the prosthetic knee were developed for evaluating the electrical damping characteristics of the DC motor in passive mode. The results showed that a single actuator could be suitable to work in active mode to provide mechanical power and in passive mode as a damper dissipating energy [2]. The semi-active prosthetic knee would be the important research direction.

We hypothesized that the plantar pressure would be bigger in the intact side. The results proved our hypothesis. The result of maximum force of forefoot and rearfoot was consistent with some previous researches. Vrieling et al. demonstrated that an increased limb-loading on the non-affected side of amputee to support balance. In amputees, vertical GRF peak in the trailing non-affected limb was higher than in the trailing prosthetic limb [24]. Rossi et al. also found significant asymmetries in the force profiles of the residual and non-amputated limbs of persons with below-knee amputation [20]. Cerqueira et al. observed decreases in vertical and anteroposterior GRF magnitudes during the propulsive phase in the amputated leg. Lower limb amputees prefer to load their weight on the intact leg. After lower limb amputations, the somatosensory input was impaired, and these balance strategies were developed by transfemoral amputees [5]. Hayashi et al. developed a novel gait motion analysis system using mobile force plate and attitude sensor. The ground reaction forces and joint moments applied on the lower limb of healthy subjects and trans-femoral amputee were measured under a wide range of environmental conditions including slope and stairs by the developed system [11]. The results were consistent with this work.

The generalization of our findings were restricted by the sample size. However, the individual trends could be explored in detail. For the next study we suggest focusing on semi-active prosthetic knee and recording the EMG in the above-knee prosthesis. We will also research the effect of microprocessor-controlled prosthetic knee with different prosthetic foot.

5. Conclusions

The developed microprocessor-controlled prosthetic knee with hydraulic damper was introduced in this work. The results of this study indicated that reduced plantar pressure were obtained in the prosthetic side. The typical butterfly diagrams were produced during different walking speeds. It indicated that the stability of the microprocessor-controlled prosthetic knee could be guaranteed.

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