CLINICAL IMPLICATIONS OF BASIC RESEARCH

Comparative Biomechanical Analysis of Current Microprocessor-Controlled Prosthetic Knee Joints

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ABSTRACT. Bellmann M, Schmalz T, Blumentritt S. Comparative biomechanical analysis of current microprocessor-controlled prosthetic knee joints. Arch Phys Med Rehabil 2010;91:644-52.

Objective: To investigate and identify functional differences of 4 microprocessor-controlled prosthetic knee joints (C-Leg, Hybrid Knee [also called Energy Knee], Rheo Knee, Adaptive 2).

Design: Tested situations were walking on level ground, on stairs and ramps; additionally, the fall prevention potentials for each design were examined. The measuring technology used included an optoelectronic camera system combined with 2 forceplates as well as a mobile spiroergometric system.

Setting: The study was conducted in a gait laboratory.

Participants: Subjects with unilateral transfemoral amputations (N=9; mobility grade, 3–4; age, 22–49y) were tested.

Interventions: Participants were fitted and tested with 4 different microprocessor-controlled knee joints.

Main Outcome Measures: Static prosthetic alignment, time distance parameters, kinematic and kinetic data and metabolic energy consumption.

Results: Compared with the Hybrid Knee and the Adaptive 2, the C-Leg offers clear advantages in the provision of adequate swing phase flexion resistances and terminal extension damping during level walking at various speeds, especially at higher walking speeds. The Rheo Knee provides sufficient terminal extension; however, swing phase flexion resistances seem to be too low. The values for metabolic energy consumption show only slight differences during level walking. The joint resistances generated for descending stairs and ramps relieve the contralateral side to varying degrees.

When walking on stairs, safety-relevant technical differences between the investigated joint types can be observed. Designs with adequate internal resistances offer stability advantages when the foot is positioned on the step. Stumble recovery tests reveal that the different knee joint designs vary in their effectiveness in preventing the patient from falling.

Conclusions: The patient benefits provided by the investigated electronic prosthetic knee joints differ considerably. The C-Leg appears to offer the amputee greater functional and safety-related advantages than the other tested knee joints. Reduced loading of the contralateral side has been demonstrated during ramp and stair descent. Metabolic energy consumption does not vary significantly between the tested knees. Hence, this parameter seems not to be a suitable criterion for assessing microprocessor-controlled knee components.

Key Words: Prostheses and implants; Rehabilitation.

IN THE PAST DECADE, a number of different electronic control concepts with different designs and functions have been integrated into prosthetic knee joints. Some joints are provided with electronic systems controlling both stance and swing phase, while in other joints, only swing phase is electronically controlled. These technologic differences result in different clinical functions for the wearer.

Biomechanical studies comparing electronically controlled prosthetic knee joints with purely mechanical alternatives have demonstrated consistent differences. When using a microprocessor-controlled knee joint during level walking, improved gait symmetry, a physiologic motion and load pattern on the prosthetic side, and load reduction on the contralateral side have been reported.[1-6] In addition, a reduction of the amputee's metabolic energy consumption has been demonstrated.[2,7-13] When descending stairs or ramps, the contralateral side is not as overloaded, resulting in a more natural pattern of motion.[14-16] Compared with mechanical components, the risk of falling after stepping onto an object or stumbling is reduced with the C-Leg.[17,18,a] These functional differences between electronic knee joints and mechanical alternatives have been documented by multiple researchers.

To date, however, few comparative biomechanical studies have been conducted. Initiation of swing phase during level walking with the Rheo Knee[b] has been reported to be easier than with the C-Leg,[10] especially for amputees with short transfemoral residual limbs.[19] When descending ramps, the C-Leg allows a smooth and physiologic gait pattern.[16] Small differences in metabolic energy consumption between the C-Leg and Rheo Knee[10] as well as C-Leg and Intelligent Knee[20] have been documented.

This biomechanical study is the first to subject prosthetic electronic knee joints to a complex functional comparative analysis. Biomechanical and metabolic parameters were measured while the amputee subjects walked on level ground, on stairs and ramps, and in situations that entail significant risk of falling.

METHODS

Data Acquisition

Components. The tests were conducted with the following knee joints: C-Leg, Hybrid Knee (also called Energy Knee[c]),

List of Abbreviations

BW	body weight

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Table 1: Principles of Resistance Generation

Joint Resistance	C-Leg	Hybrid Knee	Rheo Knee	Adaptive2
STPh-resistance	Linear hydraulic	Rotary hydraulic	Magnetorheologic principle	<35° Linear hydraulic + linear pneumatic, >35° only linear pneumatic
SWPh-resistance	Linear hydraulic	Linear pneumatic	Magnetorheologic principle	Linear pneumatic
Basic resist	Default stance	Default swing	Default swing	Default swing
Switch STPh	Electronic sensors	Mechanically	Electronic sensors	Electronic sensors
Switch SWPh	Electronic sensors	Electronic sensors	Electronic sensors	Electronic sensors

Abbreviations: STPh, stance phase; SWPh, swing phase.

Rheo Knee, and Adaptive 2.[d] The methods of creating stance and swing phase knee resistance are summarized in table 1. All prosthetic knees were tested in combination with the carbon spring foot 1C40.[a]

Subjects. Nine subjects with unilateral transfemoral amputations were recruited for this study (7 men, 2 women; mean age ± SD, 35.4±11y; mean height ± SD, 177±7cm; mean weight ± SD, 76.1±14kg; mobility grade, 3–4). The patients were experienced prosthesis wearers who routinely used the C-Leg and an ischial containment socket. All subjects had walked with various prosthetic knee joints previously and were therefore able to acclimate to different prosthetic knee joints within a short time. No amputee had any other orthopedic, neurologic, respiratory, or cardiovascular disorders. While not representative of new amputees (who tend to be older and less fit with more significant comorbidities), the tested cohort was physically able to use the full technical potential of these prosthetic devices and thereby reveal any comparative limitations. The patients' data are summarized in table 2.

Test situations. In an instrumented gait laboratory, subjects with amputation were tested under conditions that simulated the following 4 real-world situations: level walking at 3 different velocities for evaluation of swing phase quality and metabolic energy consumption, descending stairs and ramps (10° incline), and critical situations likely to cause the amputee to stumble or fall. The risk of falling was investigated in 3 different situations during walking on level ground requiring (1) abruptly stopping and sidestepping on the prosthetic side, (2) stepping onto an obstacle with the prosthetic foot, and (3) stumbling on the prosthetic side during swing phase extension.

The study was conducted in 2 phases. In 2006, the Hybrid Knee and the C-Leg were investigated, followed by Adaptive 2 (except metabolic energy consumption) and Rheo Knee in 2007 and 2008. In the second investigation phase, measurements of metabolic energy consumption with the C-Leg were repeated to investigate possible changes in the subjects' physical performance over the period of 1 year. Within the investigation phases, the knee joints were tested in random order. Each amputee completed a total of 4 test days.

Table 2: Patient Data

Subject no.	Sex	Age (y)	Height (cm)	Weight (kg)	Years Since Amputation	Cause of Amputation
1	M	39	178	75	18	Trauma
2	M	22	183	85	3	Trauma
3	M	44	178	80	29	Trauma
4	F	22	161	60	13	Osteosarcoma
5	M	42	186	85	25	Trauma
6	M	22	179	52	8	Trauma
7	M	49	173	100	23	Trauma
8	M	33	182	73	27	Trauma
9	F	46	177	75	11	Osteosarcoma

Abbreviations: F, female; M, male.

Prosthetic alignment. To allow comparative investigations of functional characteristics of the knee components, the same prosthetic foot and the corresponding individual prosthetic socket were used. In addition, prosthetic alignment of the monocentric knee joints tested in this study was identical. Following the manufacturer's instructions, the knee axis was positioned on the bench directly on the alignment reference line.[21-24] This protocol was used to eliminate functional differences that might be induced by different alignments rather than because of function of the prosthetic knee itself. [2] All prosthetic alignments and adjustments were performed by a qualified and experienced prosthetist who had successfully completed the requisite manufacturer's training for proper use all of the investigated knee joints.

Measuring technology. To measure kinematic parameters, an optoelectronic 6-camera system (VICON 460)[e] was used. To identify the joint axes, passive markers were applied to each subject in the following anatomic reference points: metatarsophalangeal joint V, malleolus lateralis (on the prosthetic side: ankle adapter screw), knee center as defined by Nietert[25] (on the prosthetic side: knee axis), trochanter major, acromion, epicondylus lateralis humeri, and processus styloideus ulnae. Ground reaction forces were measured with 2 forceplates (Kistler 9287A)[f] positioned one after another. Measurements started synchronously with the kinematic analysis. This instrumentation permitted recording of values for both amputated and nonamputated sides during the middle steps of a 12-m level walking surface and during walking on a special stair/ramp combination.[14] A telemetric spiroergometric system (Meta Max 3B)[g] was used to measure metabolic energy consumption.

Test procedure. Before starting the study, the subjects were thoroughly informed about tasks and risks of the investigations and agreed to participate in the study by signing a letter of consent.

Initially, if required, the prosthetic alignment of the subjects' daily prosthesis was optimized and documented following the alignment recommendations by Blumentritt.[26] Verifying static alignment under load on the L.A.S.A.R. Posture[a] demonstrated that the load line on the prosthetic side was located approximately 30mm anterior to the knee axis in sagittal plane. By documenting the corresponding bench alignment using the L.A.S.A.R. Assembly apparatus,[a] identical alignment of all test prostheses could be achieved. The effective heel height of the shoe, heel height and external rotation of the prosthetic foot, flexion and adduction positions of the socket, and vertical and horizontal relations of all components compared with the alignment reference line were recorded.