Comparative Biomechanical Analysis of Current Microprocessor Controlled Prosthetic Knee Joints

M. Bellmann¹, T. Schmalz, S. Blumentritt

Otto Bock HealthCare GmbH, Department of Research/Biomechanics, Duderstadt, Germany

Abstract:
In the last decades a broad range of new technologies has been integrated in prosthetic knee joints improving the functionality of prostheses supporting the rehabilitation of above knee amputees. Microprocessor and sensor based concepts allow the identification of certain walking situations and provide internal resistances to control both swing and stance phase. Movements imitating the physiological gait pattern, reduced loading of the residual loco motor system and reliable safe function in different walking situations are the main requirements upon a technically sophisticated prosthetic knee joint.

Introduction:
Following a biomechanics-based scheme, knee joint mechanisms can be divided considering design and functional opportunities influencing the degree of rehabilitation.¹ The highest mobility level is offered by so called “yielding” monocentric joint concepts allowing knee flexion under load against an internal resistance without limitation of the flexion angle. Within the group of microprocessor controlled knee joints, there are differences referring to sensor technology and the units generating internal resistances.

Figure 1: Left to right: C-Leg, Adaptive2, SynergyKnie, RheoKnee

The C-Leg system (Otto Bock, Germany) consists of a linear hydraulic unit including two independently adjustable valves for flexion and extension of the joint. For identification of certain walking situations during the gait cycle, the prosthesis is provided with an ankle moment sensor (strain gauges) installed in the tube adapter and a knee flexion angle sensor. An integrated algorithm calculates the valve positions required for adequate resistances. The working frequency of the CPU is 50 Hertz allowing adaptation of resistance each 20 ms.²

The Adaptive2 (Blatchford, Great Britain) comprehends a combination of a linear pneumatic and hydraulic unit working in parallel up to a knee flexion angle of approximately 35°. Exceeding this position, the resistance of the hydraulic unit drops to a minimum. Knee bending moments are recorded by a strain gauge sensor located posterior to the knee rotation axis, the position of the piston is determined by a stroke sensor. Motorised valves are implemented to adjust the resistances of the hydraulic
(stance phase) and pneumatic unit (swing phase) in knee flexion direction. Extension stop is adjustable by a manual valve.3
Also the SynergyKnief (Nabtesco, Japan) consists of a combination of a hydraulic and pneumatic unit. The rotation hydraulic is primarily used to produce the resistances in flexion direction during stance phase. A mechanical polycentric mechanism detecting rear and forefoot load during gait cycle allows switching from basic friction to a higher value manually adjustable. The linear pneumatic unit adapts the flexion resistance for swing phase flexion by a motorised valve based on information provided by a position sensor located at the piston and a time counter. Extension stop is manually adjustable by a needle valve.4
A rotation hydraulic unit according to a magnetorheological concept is realised in the RheoKnee (Óssur, Island). Resistance in both flexion and extension direction is produced by changing the magnetic field and resulting change of fluid viscosity. Force and moment sensors (strain gauges) installed distally to the joint chassis and a knee flexion angle sensor provide information with a frequency of 1000 Hertz. An adaptive control algorithm regulates the rate of resistances.5

Method:
To investigate performance and functionality of these differently designed microprocessor knee joints a biomechanical study was conducted under real-world conditions in a gait lab with 9 unilateral above knee amputees considering safety relevant aspects. The situations walking on level ground at three different speeds and walking down stairs and ramps were tested. In addition a defined safety test battery was conducted.6,7 During safety tests the participants were protected from falling by a harnesses.
In all situations kinematic and kinetic data and time-distance parameters were recorded. Functional comparison of the knee joints was based on consideration of extreme values of means. Measuring equipment consisted of an optoelectronical six camera system (VICON 460, Oxford Metrics, GB) in combination with two force plates (type 9287 A, Kistler, CH) to measure kinematics and kinetics.
The subjects (7m, 2f; 76±14kg; 36±11years; 177±7cm; activity level 4 = 7 patients; activity level 3 = 2 patients) were experienced walkers with high activity range able to adapt quickly to different knee joint mechanisms. They did not suffer from further limitations of the contralateral side or vascular diseases.
To eliminate the influence of different prosthetic alignments and prosthetic foot designs, identical conditions were created for all test prosthesis considering the patients’ individual optimum alignment.8

Results:
Level ground walking: Considerable differences between the knee joints referring to the quality of swing phase control were detected with respect to the adaptation to different walking velocities. One parameter for evaluation is the maximum knee flexion angle during mid swing phase covering a wide range of walking speeds. With the C-Leg, the angle increased by 11° at a walking speed growing 1m/s compared to 19 - 21° with the other joint mechanisms (figure 2 left). Another attribute for swing phase quality is the extension stop at the end of swing phase, which should be soft, as well as a continuous deceleration of knee angle velocity. A quick and hard stop was identified with the SynergyKnief already at middle walking speeds. An extension velocity strikingly low was observed with the RheoKnee. (figure 2 right).
Walking down stairs: Significant differences between the yielding concepts were observed when walking down stairs step by step referring to internal flexion resistances supporting single limb stance on the prosthetic side. Relief of the contralateral side during weight acceptance differed considerably. With the hydraulic-pneumatic hybrid design Adaptive2 the sagittal external flexion moment and hence the internal resistance were too low (figure 3 left). Unnatural high vertical ground reaction forces are generated causing high loading of the contralateral side (figure 3 right). The highest external flexion moment was measured with the linear hydraulic system C-Leg (figure 3 left). During walking down ramps nearly similar effects could be observed.

Safety tests: When the gait cycle was suddenly interrupted by an unpredictable circumstance, activation of high stance flexion resistance to load the prosthesis is of significant importance, especially in pre-flexed condition. Stepping on an obstacle with the heel and stopping on the prosthetic side was critical with the Adaptive2. This knee joint collapsed several times as the high internal flexion resistance was not activated. Provoked stumbling during swing phase extension confirmed that the C-Leg offers the highest potential to protect the amputee from falling.
Discussion:
In combination with its control algorithm, the linear hydraulic system of the C-Leg provides functional advantages over all other tested knee joint concepts in all investigated situations. During level ground walking the maximum knee flexion angle can be kept constantly at a wide range of walking speeds allowing a more natural gait pattern. The pneumatic systems of the SynergyKnie and the Adaptive2 are not able to produce the flexion resistances especially required for fast velocities. When walking down stairs and ramps the internally generated stance phase flexion resistance of the C-Leg supports a strong relief of the contralateral side confirmed by the fact that by far less subjects use the load- reducing and safe handrail walking down faster than with the other mechanisms. With the Adaptive2, it is particularly striking that, at flexion exceeding 35°, the hydraulic unit is inefficient and the pneumatic unit fails to protect the contralateral side from overloading. With the C-Leg, the flexion resistance is set to high value already during swing phase extension. This feature in combination with the integrated extension spring offers the amputee safety relevant advantages. Exact positioning of the prosthetic foot on the step becomes easier for the user, the danger of knee joint collapse is reduced as the prosthesis can be loaded in pre-flexed condition. Due to high basic friction with the RheoKnee and an insufficient extension support with the SynergyKnie, the amputees have to perform compensating movements with the hip joint to support extension of the prosthetic knee joint while walking down stairs. The C-Leg offers a high safety potential in critical situations like stumbling. After having detected disturbances of the gait cycle, the joint allows extension against a low resistance actively caused by the amputee or loading in flexed condition.

References:


Contact: Dipl.-Ing. (FH) Malte Bellmann, Email: malte.bellmann@ottobock.com