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M. Bellmann, T. Schmalz, S. Blumentritt

Functional Principles of Current Microprocessor-Controlled Prosthetic Knee Joints

Otto Bock HealthCare GmbH, Biomechanics Research, Duderstadt, Germany

This article describes the design of current microprocessor-controlled knee joints. In addition, it reports the experiences made by nine transfemoral amputees with these joint systems. Due to different designs and switching principles, the joint functions that support everyday gait situations vary. The C-Leg technology, which has been available on the market for eleven years, offers the amputee the most functional benefits.

Introduction:

Exoprosthetic knee joints can be categorised using a biomechanics-based classification. The degree of rehabilitation is determined by the functional properties of the knee component used. A high degree of mobility can be provided by the so-called single-axis „yielding“ systems. These enable knee flexion under load against a resistance

pared to purely mechanical joints, these microprocessor-controlled systems offer additional benefits to their users in various everyday situations [2-4, 7-13, 16-20, 24]. Within this group however, there are differences with regard to the sensor technologies, switching principles and designs used. In general, a distinction is made between two groups of joints: joints in which only the swing phase is controlled



Fig. 1 (from left to right): C-Leg (linear hydraulics), RheoKnee (magneto-rheological principle), Adaptive2 (hybrid design with linear hydraulics/pneumatics), Synergy knee (hybrid design with rotary hydraulics/linear pneumatics).

within the joint without limiting the knee flexion angle [1]. This yielding feature is enabled by various functional principles. In most cases, hydraulic components are used in linear or rotary designs. Another technical solution is provided by magneto-rheological concepts. In order to determine the criteria for switching between high stance phase and low swing phase resistance, microprocessor-controlled systems have increasingly been used since the 1990s to complement conventional mechanical switching arrangements. Com-

electronically and joints in which both swing and stance phase are controlled electronically.

Some of the current knee components described in the following sections use only one technical option to generate resistance, such as a linear hydraulic system (C-Leg, Otto Bock HealthCare GmbH, Germany) or a magneto-rheological design (RheoKnee, Össur, Iceland). Others include complex hybrid designs consisting of a linear pneumatic unit in combination with linear hydraulics (Adaptive2, Blatchford and Sons, Great Britain)

or rotary hydraulics (Synergy knee, also termed Energy knee and Hybrid knee, Nabtesco Ltd., Japan).

Description of the joint principles:

In the C-Leg system, which uses linear hydraulics, the hydraulic unit includes two valves for flexion and extension that can be set simultaneously and independently of each other to generate stance and swing phase resistance (see Fig. 2, bottom left). The system includes a moment sensor (strain gauge) located within the ankle tube adapter and a knee angle sensor fitted along the knee rotation axis for detecting various situations during the gait phase. On the basis of the information gathered by these sensors, two microprocessors use a specific algorithm to calculate the valve settings required to achieve adequate hydraulic resistance parameters [5]. The joint generally remains in the stance phase mode and is switched to low flexion resistance only to gently initiate swing phase flexion. This requires the knee joint under load to be fully extended in the presence of a sufficiently high dorsal extension moment of the ankle (which typically occurs in the terminal stance phase). The level of the moment to be achieved needs to be adjusted to the specific requirements of the prosthesis user. After swing phase flexion is completed, the flexion valve is set to the position of high stance phase flexion resistance immediately after a 2° extension movement. Damping of both stance and swing phase extension is set via two independent parameters. To control the swing phase, it is possible to adjust the knee flexion angle at which progressively increasing resistance sets in. This resistance is then controlled depending on the knee angle velocity. During the last stages of the extension movement, the extension stop is damped progressively and adjusted using a specific parameter.

The RheoKnee joint uses the magneto-rheological (MR) principle and generates torque that acts directly about the rotational axis. The MR fluid, which acts according to the shear principle, consists of a

suspension of oil and small iron particles. The joint head accommodates thin lamellar discs that are firmly attached to both the inner part and the outer part, which moves around the knee rotation axis. The space between the discs is very narrow (~ 20µm) and filled with the suspension (see Fig. 2, top right, magnified view on the right-hand side, grey particles in an irregular pattern). When a magnetic field is applied, the iron particles form chains that bridge the interlocking lamellar discs (see Fig. 2, top right, magnified view on the right-hand side, red particles). This results in the creation of shear forces between the discs, and thus of torque around the rotational

tance, this parameter is lowered or increased within a certain range (the lower the axial load, the lower the resistance; the higher the axial load, the higher the resistance). In this arrangement, independent resistance values can be set for both walking on level ground and walking down stairs and ramps. In order to ensure easy initiation of the swing phase, switching to a lower flexion resistance requires an extended knee joint and a certain acting knee extension moment. Swing phase flexion is damped in an adaptive fashion. A maximum knee flexion angle can be set that is to be consistently achieved irrespective of the walking speed. The damping of stance and swing

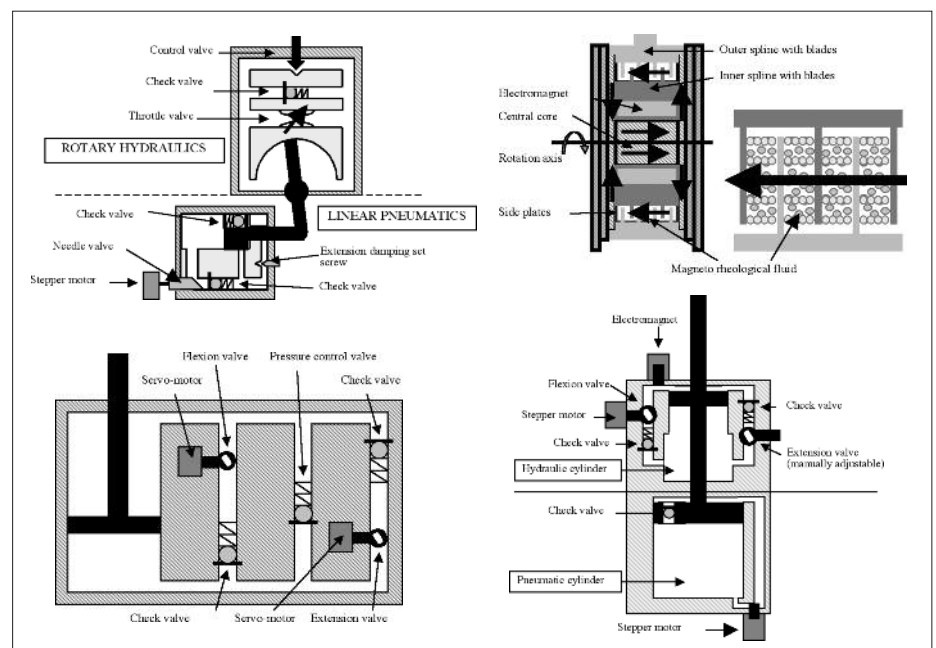


Fig. 2 Schematic representation of the joint elements that generate resistance. Top left: Synergy knee; top right: RheoKnee; bottom left: C-Leg; bottom right: Adaptive2 (modified according to [14, 21-23]).

axis of the knee joint. Similar to a drum brake, this resistance acts simultaneously in both flexion and extension direction and can be modified by the strength of the magnetic field applied. Force and moment sensors (strain gauges) mounted to the distal end of the joint chassis and a knee angle sensor fitted along the rotational axis transmit information to an adaptive control algorithm, which adjusts the resistance levels. The joint generally remains in the swing phase mode and switches to a higher flexion resistance during the stance phase, depending on the axial load applied (F_x). Starting from an adjustable „mean“ resis-

phase extension can be adjusted separately. In addition, the system has an auto-adaptive learning mode that adjusts the joint to the prosthesis user's usual gait or changes to it. [6].

The Adaptive2 hybrid design includes a linear pneumatic and a linear hydraulic unit. These units act simultaneously at a knee flexion angle of up to approx. 35°. The pistons of both units are mounted on one axle, and are included in separate cylinders in the same housing (see Fig. 2, bottom right).

Hydraulic unit: The diameter of the hydraulic cylinder varies. It is larger in its rear half in the direction of insertion. When the piston

has reached this position, oil is no longer displaced and resistance is reduced to a minimum. As a result, only the pneumatic unit continues to act in the following flexion stages. Motor-driven valves set the resistance parameters of the hydraulic unit (stance phase) only in the direction of flexion. Adjustable resistance is available for both stance and swing phase extension. This resistance can be adjusted manually via a needle valve integrated in the hydraulic unit.

Pneumatic unit: A motor-driven needle valve is used to generate the pneumatic resistance that acts mainly in the swing phase. This valve adjusts resistance values for swing phase flexion depending on walking speed. The cushion generated in the flexion phase by compressing the air is used to store energy; it re-expands to support the ensuing extension movement. This eliminates the need for a mechanical extension spring.

Two integrated sensors detect the individual gait phases. Moments acting in the direction of knee flexion are captured by a force sensor (strain gauge) fitted posterior to the knee joint axis. The insertion position of the pistons is recorded by a position sensor. The duration of the stance phase is used to derive the walking speed and the specific gait situation. If required, both pneumatic and hydraulic resistance parameters are set. The joint is generally in the swing phase mode and will switch to higher flexion resistance only when knee flexion moments start to act. This resistance can be independently adjusted for walking down stairs and ramps. In addition, the joint features a stumble mode that switches to a different, separately adjustable flexion resistance when gait cycle disruptions are detected [25].

Another hybrid design is the Synergy knee, which combines rotary hydraulics with linear pneumatics. The joint head is formed from the hydraulic unit and is functionally coupled to the pneumatic unit by a piston rod. A polycentric mechanism connects the joint head to the lower section and also functions as a hydraulic unit switch (see Fig. 2, top left).

Hydraulic unit: This component

is used exclusively to provide resistance in the direction of flexion during the stance phase. It is activated mechanically. The polycentric mechanism projects its instantaneous centre of rotation to the forefoot area, and a distinction can be made between forefoot and hindfoot load. When the hindfoot makes ground contact, a high, manually adjustable stance phase value can be activated. There is low basic friction when the forefoot makes contact with the ground. The configuration of the polycentric system, and thus the position of the instantaneous centre of rotation, can be adjusted to modify the sensitivity of the threshold. The joint is generally in the swing phase mode. The mechanically operated polycentric mechanism switches the joint to a higher stance phase flexion resistance depending on the position of the ground reaction force on the prosthetic foot.

Pneumatic unit: The linear pneumatic system acts in conjunction with a microprocessor and uses a motor-driven valve to adjust the swing-phase flexion resistance. Depending on the walking speed, this adjustment is made on the basis of the information gathered by a position sensor mounted to the piston and a time counter. The measured duration of the swing phase is used to set a certain valve parameter in the pneumatic unit for the swing phase flexion of the following step. The air compressed during swing phase flexion is used to support swing phase extension. Both in the swing and the stance phase, the degree of damping of the extension movement can be adjusted manually using a needle valve [15].

Table 1 provides an overview of the design and switching principles of the knee components described above.

Experience made with these knee joint mechanisms

Reports on the experience of nine unilateral transfemoral amputees were published. This information was gathered from both trial and final fittings, as well as from tests that were carried out

under laboratory conditions. The joint parameters were set in accordance with the manufacturers' recommendations.

Walking on level ground:

Efficient swing phase controls keep the maximum knee flexion angle at a relatively constant level, ranging from 60 to 65° for various walking speeds during the mid-swing phase. This corresponds to the natural gait pattern.

The pneumatic swing phase control systems used in the Synergy and Adaptive2 joints set the valve to a certain position at the beginning of the swing phase, where it then remains. An air cushion is compressed continuously during the entire flexion movement. At higher walking speeds, the resistance thus generated is not sufficient for flexion damping, which results in an unnaturally large knee flexion angle in the mid-swing phase. The increase in the maximum knee flexion angles in line with the increase in walking speed is shown for all four joints in Fig. 3, left.

The energy stored in the air cushion supports the extension movement in the swing phase. Setting a high flexion damping level to achieve a natural knee angle results in greater support for the extension movement. This results in a rapid extension movement and thus usually a hard, uncomfortable extension stop. At low walking speeds, the degree of compression is also low, which is why the extension movement is supported less strongly. If the extension stop damping is also set to a high level in order to achieve a more comfortable damping effect at high walking speeds, the joints may not be able to reach their extended position. In the Synergy knee, a manually adjustable air cushion provides the end position damping, which proves to be weak during fast walking. In the Adaptive2 joint, hydraulic damping is activated abruptly when the 35° flexion angle is exceeded, which the user perceives as out-of-sync and unsteady behaviour. This phenomenon is illustrated in the right diagram of Fig. 3, which shows the knee angle velocity over the time of extension.

In this regard, the RheoKnee

	C-Leg	Synergy Knee	RheoKnee	Adaptive 2
STPh resist.	linear hydraulics	rotary hydraulics	magneto-rheological principle	< 35° linear hydraulic + linear pneumatics, >35° only linear pneumatics
SWPh resist.	linear hydraulics	linear pneumatics	magneto-rheological principle	linear pneumatics
Basic resist.	default stance	default swing	default swing	default swing
STPh switch	electr. sensors	nechanical	electr. sensors	electr. sensors
SWPh switch	electr. sensors	electr. sensors	electr. sensors	electr. sensors

Table 1 Overview of design and switching principles of knee joints (STPh: stance phase, SWPh: swing phase, resist.: resistance)

and, in particular, the C-Leg provide advantages. In these joints, resistance parameters can be adjusted in near real time as and when required for very specific stages of the swing phase movement. As a result, the stop at the end of the extension movement can be damped progressively, even at high walking speeds, in a manner not noticeable to the user.

Walking on stairs and ramps:

To walk down stairs and ramps step-over-step, it is important to position the prosthetic foot accurately on the ground (in particular on the steps) and to ensure the stability of the prosthesis system during the single-leg stance phase. Systems with a sufficiently high internal extension support make it easier for their users to tread onto the step with an extended prosthesis whilst positioning the middle of the foot on the edge of the step. In general, extension in the swing phase progresses more slowly in these situations than when walking on level ground. For this reason, the Synergy knee and the Adaptive2 joint cannot make use of the benefits offered by the extension support provided by the air cushion. At the same time, the end position damping set for walking on level ground may be too high for walking on stairs so that the prosthesis does not reach its extended position. The RheoKnee appears to provide a high level of basic friction, delaying the slow extension movement even further. As a result, these three systems are already in movement immediately prior to making contact with the step, which may give the user an impression of instability or insecurity

during this extremely complex sequence of movements. If, in addition, the forefoot of the prosthesis with the flexed Synergy knee is positioned on the step, the low swing phase resistance may remain activated, in which case the prosthesis will collapse under load. Due to the limited extension support provided by the Adaptive2, Synergy and RheoKnee joints, additional residual limb movements are required for compensation purposes to support the extension movement of the prosthetic knee joint when walking down stairs.

The internal stance phase flexion resistance levels provided show significant differences in several cases. The left diagram of Fig. 4 shows these values for all four joints, using the sagittal knee moments. The Adaptive2 joint provides high hydraulic resistance only up to a flexion of 35°. Thereafter, the movement is influenced only by the pneumatic swing phase resistance. This transition between the two types of resistance occurs very abruptly, still in the single-leg stance phase, and can be compensated only to a very limited extent by residual limb activity. This leads to a hard heel strike on the contralateral side, which is shown in the right diagram of Fig. 4 by means of vertical ground reaction forces. The RheoKnee activates the stance phase flexion resistance depending on the axial load. The resistance will be lower if the user treads on the step more cautiously. This, in turn, increases the level of insecurity over and above the inaccurate positioning of the prosthetic foot, particularly in users with limited motor abilities. Moreover, the resistance that can

be generated internally appears to be limited, which clearly shows in users at the upper weight limit (100 kg), who sense a slight „jerk-ing“ within the joint. In these situations, the Synergy knee and the C-Leg provide sufficiently high resistance levels that come very close to the physiological pattern across a wide range of flexion. In addition, the C-Leg provides added safety because its high stance phase resistance in the direction of flexion remains activated in these gait situations. This means that the prosthesis can be loaded even in its flexed position in the event of any movement disruption.

Situations involving the risk of falling when walking on level ground

For the systems presented in this article, safely stepping on an obstacle depends on the position of the obstacle underneath the prosthetic foot. The forefoot area does not pose any problem because the ground reaction force acts in a line anterior to the knee rotation axis. If the obstacle is located in the heel or rear mid-foot area, all systems will switch to high stance phase flexion resistance, or are activated already (C-Leg). In the case of the Adaptive2 joint, this may lead to a situation in which switching to the high, stabilizing flexion resistance does not occur upon initial ground contact. The knee joint starts to flex immediately, and the resistance is activated late or not at all. As a consequence, the ground reaction force vector, which acts posteriorly, will cause the prosthesis to collapse at the time of loading.

In all designs, almost no problems arise when it comes to

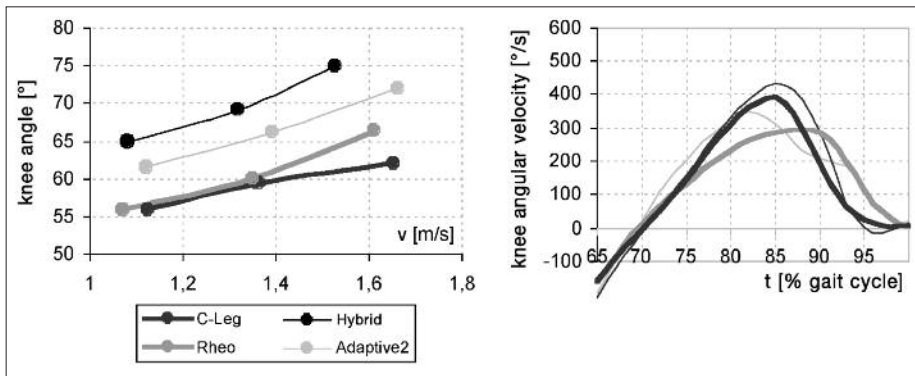


Fig. 3 Maximum knee flexion angle at low, medium and high walking speed during walking on level ground (left), knee angle velocity during the swing phase at medium speed (right).

abruptly stopping or negotiating obstacles on the prosthesis side. All systems already work with the activated high stance phase flexion resistance or switch to it, enabling loading of the prosthesis. If, however, this load is applied cautiously or hesitantly, the RheoKnee switches to a relatively low resistance not adjusted to the situation. The Adaptive2 joint may not switch at all under certain conditions, which makes it more difficult for the user to safely load the prosthesis because the residual

but also on the performance of the residual limb. Among other factors, this includes the user's ability to respond and his/her muscular or motor abilities. The most deeply rooted strategy to respond to stumbling is to secure the prosthesis actively by an immediate residual limb extension – as far as possible even prior to ground contact. If this response is too slow, which makes it impossible to actively extend the prosthesis, the prosthesis must be capable of being loaded in flexion. This applies to unex-

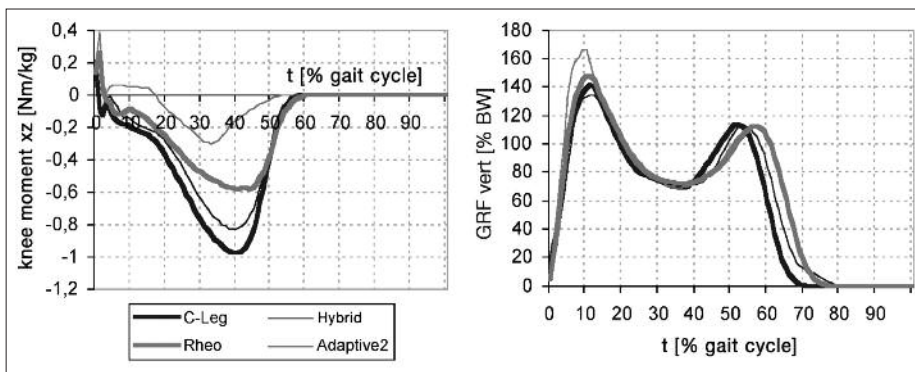


Fig. 4 External sagittal knee moment on the prosthesis side when walking down stairs (left), vertical ground reaction forces on the contralateral side (right).

limb is unable to extend to stabilise the prosthesis in this situation. If this movement were carried out, it would move the body's centre of gravity in anterior direction, contrary to the requirement. In this regard, the C-Leg offers some advantages because the high resistance is already activated prior to ground contact, which enables loading of the prosthesis at any time.

The ability to avoid a fall after a disruption of the swing phase extension that may be caused by stumbling or tripping with the tip of the toe depends on the technical characteristics of the knee joint

pected situations in particular. In this regard, it is important that the prosthetic knee joint can be slightly extended or that the flexed prosthesis can be loaded. The only system that provides these features on a consistent basis is the C-Leg. All other designs first need to be switched after the disruption, which depends on various conditions that are not given in some cases. Following the disruption, the Synergy knee is switched to high stance phase resistance. However, if the user responds by the routine movement pattern, i.e. by extending the residual limb, this may result in switching back to the

low swing phase resistance. The system will collapse if the prosthesis is also loaded in the forefoot area. The Adaptive2 joint is switched to high flexion resistance only if the disruption occurs almost at the end of the swing phase extension. If the disruption occurs at an earlier stage, this system will also collapse. The RheoKnee switches to high flexion and extension resistance in a direct, quick and reliable manner if any disruption to the swing phase extension occurs. If the user responds by his/her routine pattern, i.e. by an immediate, quick residual limb extension, he/she moves the prosthesis backwards and loads the prosthesis with his/her foot that is significantly shifted in posterior direction. This situation poses the risk of slipping.

Summary

For practical use, the micro-processor-controlled knee joints presented in this article provide a varying range of features, which can be attributed to the differences in their technical implementation. What is crucial is not only the design for generating internal joint resistance levels but also the principles of switching between high and low flexion resistance values. The C-Leg provides functional benefits in many everyday situations. This is due to the fact that the required resistances are activated by a reliable, easy-to-use switching and sensor system. Its pre-set stance phase resistance provides the amputee with the best possible technical prerequisites to prevent falling, especially in critical situations that require complex motor activity.

For the authors:

Dipl.-Ing. (FH) Malte Bellmann,
CPO-D
Otto Bock HealthCare GmbH,
Research
Hermann-Rein-Str. 2a
37075 Göttingen, Germany

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