# An inverted multi-axial knee-prosthesis: influences on gait

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## Introduction

People who have undergone trans-femoral amputation will often be provided with an Above-Knee Prosthesis. Even so, their gait pattern, being originally symmetric, will change significantly. The main causes of this effect are the altered kinetics and kinematics.

Firstly, the prosthesis does not match the healthy leg kinetically. In normal walking, during the end of the push-off phase and the beginning of the swing phase a hip flexion moment is exerted. This moment is in the same direction as the angular velocity of the thigh, which means energy is generated. In the prosthetic leg, usually a hip extension moment is exerted during the complete stance period. Thus, energy is dissipated during push-off. At the moment of toe-off, the hip moment must change direction abruptly to enable the forward swing.

Secondly, the kinematics of the prosthesis does not match the healthy leg. For instance, during push-off the healthy leg will elongate slightly, enabling extended support of the trunk. Most of the existing prostheses will, after a slight initial elongation during the first few degrees of flexion, shorten substantially. An advantage of this behavior is good ground clearance during swing. However, a major drawback is reduction of the push-off phase on the prosthetic side.

## Methods

Both problems can be solved by a proper placement of the knee Center Of Rotation (COR). To determine this position a biomechanical analysis has been performed.

As has been noted by various authors (e.g. Radcliffe, 1994), it is advantageous for static stability reasons to have an elevated and somewhat posteriorly placed initial location of the COR during stance. ‘Static stability’ entails the property that when the prosthetic user exerts no hip moment while standing on the prosthesis, the knee joint will automatically return to the fully extended position (or remain in a locked position). This is a desirable condition, during all phases of standing. However, it is not a sufficient condition for a stable push-off. During push-off, when the knee is flexed, the COR will move forward and thus towards the stability-line, decreasing the stability angle $\alpha$ (*figure 1*). This effect will be more pronounced in the four-bar linkages, in which during knee flexion the COR generally moves anteriorly and downward, ending up somewhere inside the knee mechanism. As the hip flexion moment required for maintaining static equilibrium is dependent on the stability angle $\alpha$, this moment decreases with increasing knee (and hip-) flexion angle. It is known from control theory that such a system in which the required output (in this case the hip flexion moment) is inversely related to the control variable (flexion angle) is extremely hard to control. More desirable would be a knee mechanism in which the COR would move backwards, slightly increasing $\alpha$ during the first stage of knee flexion.

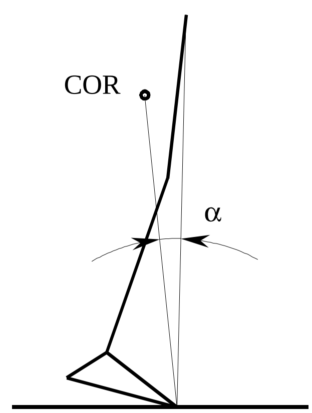


**Figure 1: stability during push-off**

Kinetically, we actually have conflicting demands. On the one hand it would be desirable to have lengthening of the prosthetic leg during push-off, since this would enable the prosthetic user to extend the push-off phase as in normal walking. On the other hand, during the swing phase shortening of the effective leg length would be required in order to prevent the toe from hitting the ground, which could cause stumbling of the prosthetic user. Such shortening can only be obtained when the COR is located anteriorly of the imaginary line connecting the toes and the hip joint.

Thus we can conclude that a dynamically stable knee hinge should have a COR which initially moves in posterior direction during knee flexion, but which reverses this direction of movement as soon as certain flexion angle has been reached.

**Results**

A knee hinge with a polar curve (path of COR) exhibiting the desired behavior has been designed. Basically it is a four-bar type mechanism. However, the lower (tibial) portion of the prosthetic leg is not connected to the lower horizontal bar but to the upper horizontal member. The prosthetic socket is fixed to the lower horizontal bar. This inverse mechanism results in a polar curve which initially is directed posteriorly, and then towards the knee mechanism (*figure 2*). Clinical trials with a prototype showed an increase of the prosthetic push-off time as well as a decrease of the peak hip moments on the prosthetic side (Hendriks, internal report).

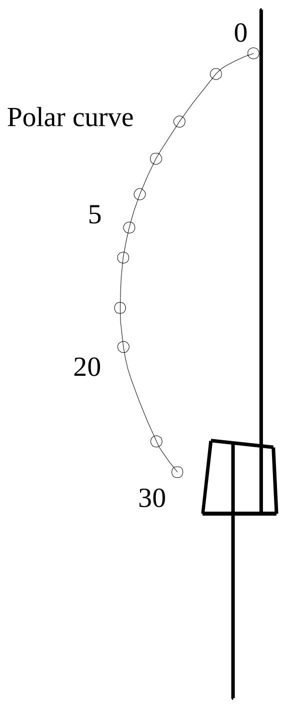


**Figure 2: inverted four-bar mechanism with polar curve. COR depicted at various knee flexion angles.**

At the same time, the trials also showed that extension of the leg was excessive, causing the prosthetic user to hit the ground during swing of the prosthetic foot. As the stability during stance and push-off was indicated as favorable, a new design was made, based on the same premises (COR moving posterior and downwards) but with less lengthening of the leg. The knee hinge is a six-bar Stephenson-1 type of mechanism. As can be seen in *figure 3)*, the COR initially moves towards posterior as it does in the inverted four-bar mechanism. However, after approximately 6 degrees of knee flexion the COR rapidly advances towards the knee mechanism where it remains with increasing knee flexion.

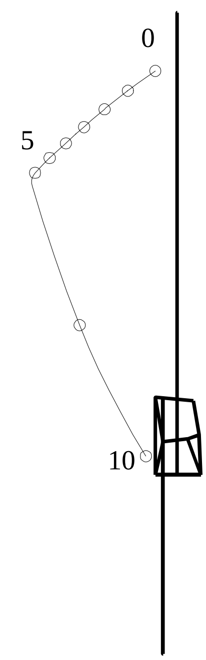


**Figure 3: inverted six-bar mechanism with polar curve. COR at various knee flexion angles.**

To evaluate leg length during knee flexion of the two prototypes, they were incorporated in a segmental model. Reference knee was a uni-axial knee hinge. Average dimensional parameters of upper and lower leg as well as from the foot were taken from Koopman (1989). Effective leg length, defined as the distance between toe and hip joint, was plotted as a function of knee flexion angle, see *figure 4a)*. As can be seen, initially leg length increases equally for both multi-axial hinges. At approximately 10 degrees of knee flexion lengthening of the leg with the 6-bar hinge starts leveling off and follows the uni-axial curve at a 7-mm offset.

As noted before, the hip flexion moment required for knee flexion depends on the angle between the line *toe-hip* and the line *toe-COR*. *Figure 4b)* shows this angle as a function of knee flexion angle for the uni-axial hinge and for the two inverse hinges. As can be seen, the uni-axial hinge is statically stable but the necessary flexion moment decreases with increasing knee flexion. For both multi-axial hinges an increasing hip flexion moment is needed to increase initial flexion. This greatly facilitates control during the push-off phase.

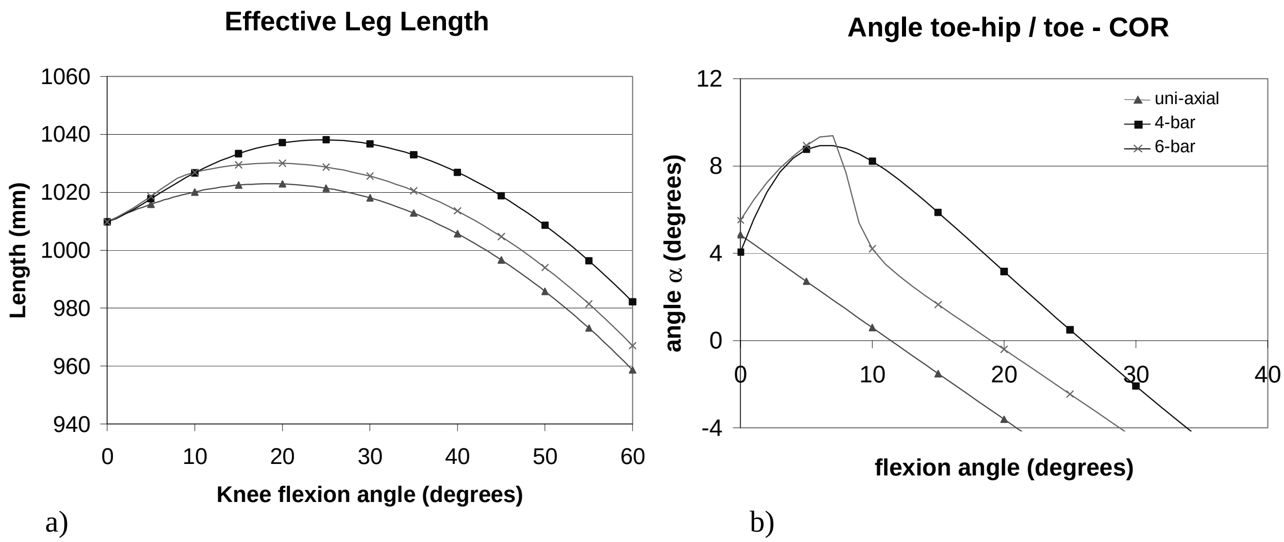


**Figure 4: Effective leg length (a) and angle between lines through toe-hip and toe-COR (b) as a function of knee flexion angle**

## Discussion

The new 6-bar prosthesis will allow an extended push-off. This is expected to increase energy efficiency and to make the gait pattern of a unilateral prosthetic user more symmetric. Also, push-off has been shown to be stable, requiring increasing hip flexion moment with increasing flexion angle. A possible negative side-effect caused by posterior placement of the path of the COR would be excessive lengthening of the leg during swing. This effect is minimized by the rapid progression towards the knee of the instantaneous center of rotation after push-off.

## References


Koopman The Three-Dimensional Analysis and Prediction of Human Walking, FEBO, Enschede 1989

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