KINETIC VERSUS KINEMATIC STRATEGIES IN PROSTHETIC STANCE-PHASE CONTROL

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INTRODUCTION

Most individuals with above-knee amputations rely on prosthetic stance-phase control for stability during weight bearing, and therefore safe and efficient gait. Stance-phase control is primarily achieved geometrically using four, five, and six-bar linkages, hydraulically using dampers, and kinetically using frictional brakes[1-6]. The latter, offering relatively simple implementation, is of interest for use in applications where size, weight, and cost constraints exist, namely in the prescription of prostheses for paediatric and geriatric patients[1].

The weight-activated safety knee joint is a prevalent commercial example of a kinetic-based stance-phase controller. It consists of the main knee flexion axis that is comprised of a shaft and split bushing, the latter of which squeezes the former to apply braking. Braking is produced as a result of loading at a secondary axis, termed the control axis, either due to a flexion moment or in part a compressive force on the prosthesis. One drawback of this approach is that the user must entirely unload the prosthesis to initiate swing flexion, which results in slower and more cumbersome gait[1]. Consequently, these types of systems are predominantly prescribed for geriatric patients.

One design option for releasing the brake towards the end of the stance-phase is by reorienting the control axis, specifically, by moving the axis distally of the main knee axis[7]. In this way, toward the end of stance-phase as a forefoot centre of pressure develops, an extension moment at the secondary axis deactivates the brake. This strategy facilitates a smooth transition into swing-phase and therefore is potentially suitable for use in the prostheses of young and active users.

However, as with all systems that are reliant on frictional braking achieving reliable stance-phase control can be a challenge due to fluctuations in the coefficient of friction. For this reason, it is of interest to investigate variations of the aforementioned system that are not friction-based, but rather motion-based, or kinematic-based. It was the focus of this work to apply the stance-phase control strategy, within the context of a kinetic-based mechanism, and also a kinematic-based mechanism, so as to facilitate a comparative evaluation. In this regard, the theoretical principles and empirical data obtained from clinical testing are presented here.

BACKGROUND

With respect to the implementation of the stance-phase strategies into an articulating knee joint, three elements are essential, including a means of resisting knee flexion such as a brake or a latch (A), means for signal input such as a control axis (B), and a mechanism for transmitting the input signal to the braking or latching mechanism (C and D). In the case of a kinetic-based system, the mechanism (C and D) transmits the forces or moments generated at the control axis, whereas in the kinematic-based system, motions are transmitted. Therefore, the kinetic-based system works on the principle of transmission of large loads and small motions, and the kinematic-based system works on low loads and relatively large motions. Figure 1 illustrates exemplary implementations of the kinetic and kinematic-based concepts, shown in the locked and unlocked conditions. Table 1 provides a comparative analysis of the physical characteristics associated with each control option.

Whereas the kinetic-based system is advantageous in that it facilitates locking under flexion, locking can only be initiated as a result of limb loading. During the swing-phase the braking must be biased to deactivate. In contrast, the kinematic-based approach offers single position locking. As it cannot lock during swing-phase except for when it is fully extended, it may be biased to engage when there is no load. For greater user safety, this produces locking at the end of swing-phase, prior to weight bearing, and not as a result of weight bearing.

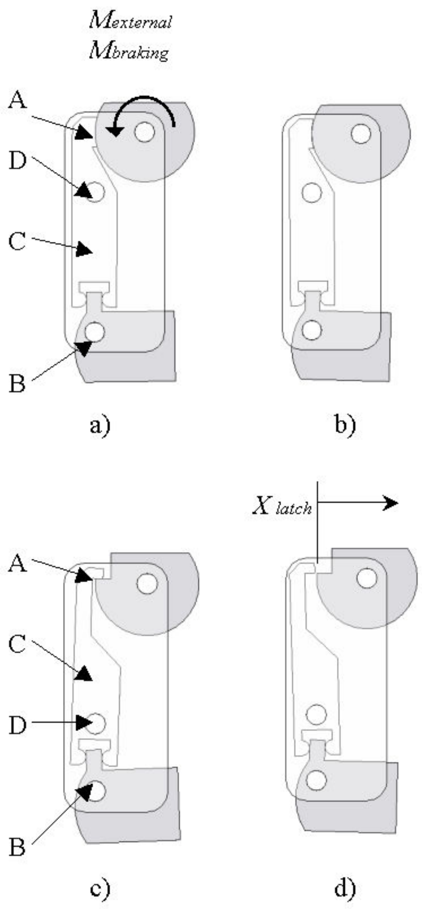

Figure 1: Kinetic-based concept: a) locked, b) unlocked; Kinematic-based concept: c) locked, d) unlocked. A – lock/latch, B – control axis, C – signal transmission part, D – rotational/amplification axis

METHODOLOGY

Participant: Physically active 12-year old male with a congenital, unilateral, above-knee limb deficiency resulting in amputation.

Intervention: Prototype knee joints, incorporating kinetic and kinematic-based stance-phase control mechanisms, were fabricated. The kinetic-based version utilized a band brake comprising of a split bushing concentric to a ground shaft. Adjustment for the braking torque was provided in the design. The kinematic-based version was similar in concept to the one depicted in figure 1. The mechanism incorporated a spring to bias the latch into the engaged position when the knee was in full extension. Provision was made for the adjustment of force amplification in the kinetic-based prototype, and for motion amplification in the kinematic-based knee prototype. Both prototypes were mechanically tested to ensure structural integrity.

Procedure: A duplicate of the participant's regular prosthetic limb was fabricated by a certified prosthetist and the prototype knee incorporated. Prior to testing, alignments were checked and prototype knee joint was tuned to provide optimal stance-phase control for the participant. Short-term testing was comprised of the participant using the knee for 30 to 60 minutes indoors within a laboratory setting. Subsequently, long-term testing was performed over a four-week period, during which time the user took the device home to wear and use as part of his daily life. Testing was first performed with the kinetic-based knee prototype, and then repeated for the kinematic-based prototype. The researcher or prosthetist followed up with the

Table 1: Physical and functional characteristics of kinetic and kinematic-based knee joints

	Kinetic-based	Kinematic-based
Stabilization means	Frictional brake	Latch member
Signals	Forces/moments	Motions (linear/rotational)
Stabilization positions	Infinite (continuous)	Single position (discontinuous)
Destabilization criteria (@ knee axis)	$M_{brake} = 0$	$x_{latch} = 0$
Stabilization criteria (@ knee axis)	$M_{brake} > M_{external}$	$x_{latch} > 0$
Transmission mechanism	Provides kinetic amplification by proximal placement of rotational axis (labeled D in Figure 1)	Provides kinematic amplification by distal placement of rotational axis (labeled D in Figure 1)
Latch/brake status under no load	Brake must be deactivated with no load	The latch may be biased to engage under no load

participant to ensure optimal operation of the knee joints during testing. At the end of the testing period, an unstructured interview was conducted to ascertain the performance of the respective components. Informed consent was obtained prior to testing.

RESULTS

Table 2 summarizes the information acquired during both, the short-term and long-term testing, including those data collected during the interviews. Items 1 and 3 were evaluated predominantly during the short-term testing, items 2 and 6 during the long-term testing, and items 4 and 5, during both.

DISCUSSION

During the short-term lab testing, both prototypes exhibited excellent stance-phase control characteristics. Both were easily tuned to the individual's stability requirements. During field-testing, however, the kinetic-based system operated unreliably. Under certain circumstances, the braking mechanism either failed to provide adequate braking, thus resulting in a stumble or fall, or it inadvertently locked during the swing-phase, also resulting in a stumble. The problem was most prevalent during temperature fluctuations, for example the user going outdoors in the wintertime. One possible explanation was the influence of condensation on the coefficient of friction. A variety of bushing materials were tested including bronze, graphite-filled bronze and a composite material. Shafts comprised of ground stainless steel (17-4 Ph, condition 1100), hardened stainless steel (17-4 Ph, condition 900), and hard chromium-molybdenum plated steel. Testing with this prototype was discontinued prematurely at 2 ½ weeks, due to the high frequency of falls experienced by the participant (Table 2, item 6).

In contrast, field-testing with the kinematic-based prototype was more successful, largely due to the reliable function of the stance-phase control mechanism. Early on in the testing, the latch seized up, but the problem was alleviated using an alternate bearing material. The participant reported a much lower incidence of falls with this prototype than with the kinetic-based one. This suggests that the strategy for locking the knee at the end of swing-phase is effective. Considering the braking reliability issues associated with the kinetic-based prototype, the kinematic-based system is likely the better option for use in prosthetic stance-phase control.

One common and important tuning parameter is the mechanical amplification of the signals, forces, and motions for the kinetic-based and kinematic-based systems, respectively. For the kinetic-based knee, excessive amplification results in inadvertent and undesirable locking of the knee during the swing-

Table 2: Summary of data from the short-term and long-term clinical testing

Item	Item Description	Kinetic-based	Kinematic-based
1	Effectiveness of stance-phase control	Very effective	Very effective
2	Reliability of stance-phase control	Low	High
3	Adjustment of stance-phase control	Relatively easy – a screw that adjusts 'no load' braking force	Relatively easy – screw that adjusts latch bias spring
4	Perception of stability	Excellent - when locked, the knee provides solid support	Excellent - When locked the knee provides solid support, but the small amount of angular rotation at the control axis takes some getting used to
5	Effect of amplification of signal	- Excessive amplification causes locking during the swing-phase - Insufficient amplification causes knee instability during loading	- Excessive amplification prevents latch disengagement -Insufficient amplification excessive rotation at control axis
6	Frequency of falls due to knee instability	1 per day	4 per month

phase. Conversely, insufficient amplification results in inadequate braking. For the kinematic-based system, excessive amplification results in forces that are too low to overcome the latch bias force and the minute frictional resistance of the system, and consequently obstinate latch disengagement. Finally, low amplification causes more rotation at the control axis, and results in the perception of wobbliness or instability.

While the activation and deactivation of the latch/brake is one source of motion at the control axis, excessive tolerances between the mechanical linkages, and the natural strain of materials under stress add to the generally undesirable motion between the shank and thigh components during stance. During testing, the participant initially noted this wobbliness, and perceived it as instability. Within a short period of time, however, the user became quite comfortable with this, as he realized it was not related to knee collapse.

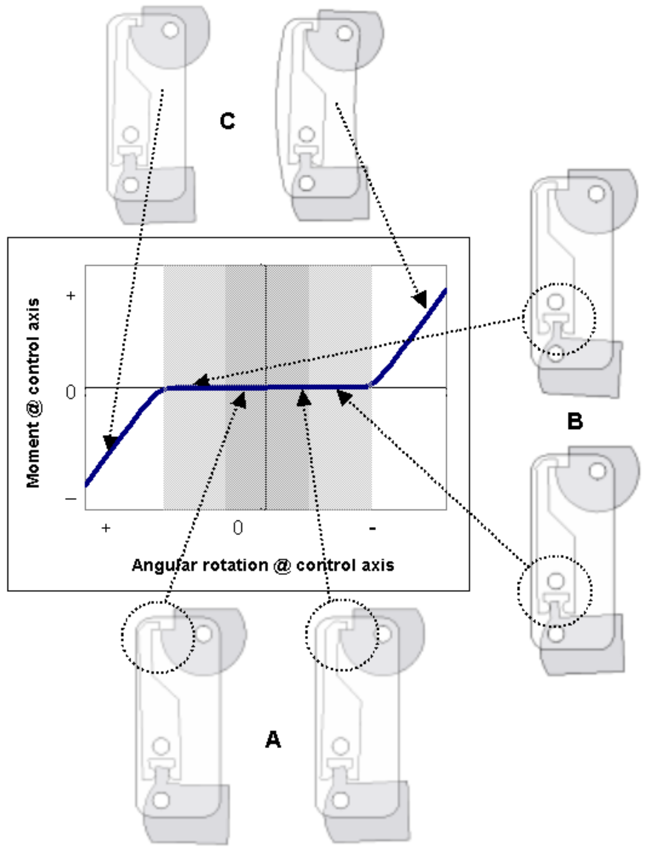

Figure 2: Idealized motions versus moments at the control axis as a result of: A – brake/latch engagement and disengagement, B – loose tolerances in transmission mechanism, C – stress induced strain of materials.

CONCLUSIONS

A unique new approach for stance-phase control utilized a kinematic-based locking mechanism, that was fundamentally similar to a kinetic-based mechanism comprised of a source of signal input (control-axis), a transmission means, and brake/lock means. Similar approaches to assess fundamental mechanical equivalents may be useful in other instances where more effective mechanisms are being sought. Unlike the kinetic-based stance-phase control system that utilized large forces and small displacements, the new kinematic-based system utilized low forces and relatively large motions. The benefits of this approach include reduced internal loads in the mechanism, which may lead to the development of smaller, lighter weight and more durable prosthetic knee joint components. Furthermore, the disadvantage of single-position locking may be offset by the increased stability that is achieved by locking the knee prior to weight bearing. During clinical testing the kinematic-based approach was shown to be highly reliable, and until materials with more consistent braking properties become available, the kinematic-based approach is a preferred stance-phase control means.

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