Mechanical Component Optimization, Design and Preliminary Testing of a Fully Passive Prosthetic Knee Mechanism

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BACKGROUND

An estimated nine-million above-knee amputees are in need of prosthetic devices in developing countries across the world [1]. A majority of them face unique and severe socio-economic constraints in their daily lives [1]. Although knee prostheses used in developing countries are mechanically robust, they are typically passive and have inherent biomechanical performance limitations due to their design architecture [2]. The choice of low-cost components in these devices has been primarily driven by the need for stability during the stance phase of gait. This results in undesirable deviations from able-bodied kinematics, both during stance and swing phases of gait [2].

AIM

We present an inverse dynamics approach to select optimal mechanical components to enable the knee moment required for able-bodied kinematics of level ground walking. We also propose a novel architecture of the knee mechanism with timely engagement and disengagement of the chosen mechanical components to achieve reliable stance and swing phase control.

METHODS AND RESULTS

Analysis: A four link-segment rigid body model of the prosthetic leg was designed with one spring and two dampers at the knee joint. Both zero-order (friction) and first-order (viscous) dampers were considered. Inverse dynamics was performed to estimate the knee moment required for achieving normative joint kinematics at the hip, knee and ankle by the optimal engagement of spring and dampers [3, 4]. Results for this analysis are shown in Fig. 1.

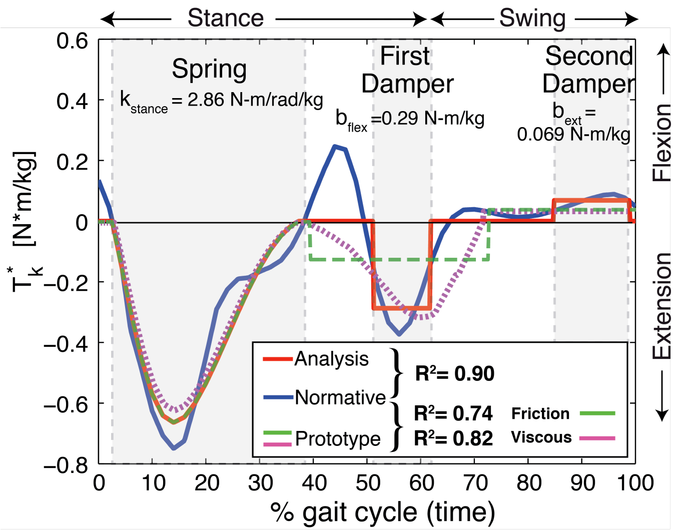

Figure 1. Replication of knee moment (T^*_k) to enable able-bodied kinematics: The blue curve is the modified normative moment profile to generate able-bodied kinematics in a prosthetic leg with characteristic mass properties [3]. The red curve shows that a single linear spring (*k_stance*) and two zero-order dampers (*b_flex* and *b_ext*) would closely replicate the modified normative moment profile, with R^2=0.90. The green dashed curve is the predicted response of the knee prototype shown in Fig. 2 (R^2=0.74). The magenta dashed curve is the predicted moment response from a similar architecture with 'smoother', viscous dampers for late stance flexion and swing extension (R^2=0.82), instead of the friction dampers.

Design: The prototype knee mechanism was implemented using an automatic early stance lock for stability, a linear spring for early stance flexion-extension and a rotary damping system for late-stance and swing control [5]. For preliminary validation, we tested the prototype on four above-knee amputees in India. The two-minute walk test was conducted and qualitative feedback was sought from the subjects. Results in Fig. 2.

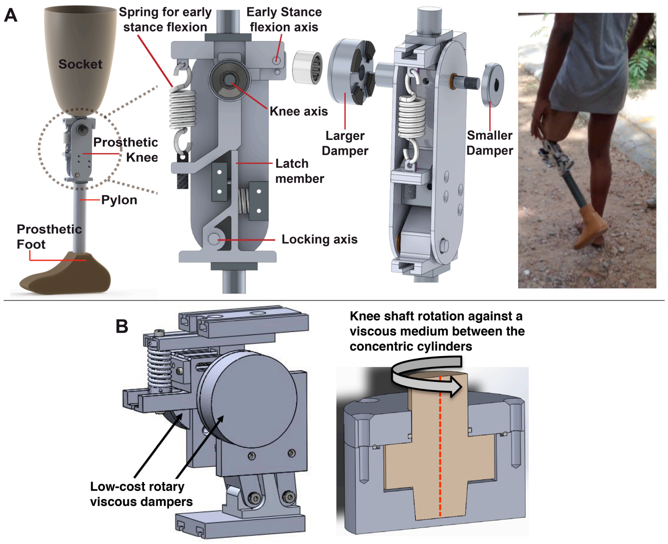

Figure 2. A. Preliminary prosthetic knee prototype with (i) friction-based dampers for late-stance control and swing control, and (ii) spring for early stance flexion-extension. The preliminary field trial on four above-knee amputees in India showed satisfactory performance of the early stance lock for smooth stance to swing transition. B. Prototype with rotary viscous damping was implemented. The stick-slip behaviour of the friction-brake pads during testing and better-predicted performance of the first order dampers (Fig. 1) informed the decision to use viscous dampers in this improved iteration.

DISCUSSION

An important design strategy for this prototype mechanism was to use the movement of the centre-of-pressure from the heel to the toe, and the resulting change in the direction of the GRF vector. This movement served as an indicator of progression of the stance phase, which was used to translate our analysis (Fig. 1) into a novel embodiment that could replicate the required knee moment (Fig. 2) by timely engagement of the optimal spring and dampers. The stick-slip behaviour of the friction-brake pads strongly indicated the need to use low-cost viscous dampers. The primary limitations of this study are the assumption of able-bodied ankle behaviour and the pending quantitative validation of kinematic performance (on-going). However, the analysis and the modular mechanisms presented here are useful as a starting point for the design of low-cost, passive prosthetic knees in the future.

REFERENCES

1. Hamner et al., "Designing for scale: Development of the remotion knee for global emerging markets." *Annals of Biomedical Engineering* (2013)
2. J. Andrysek, "Lower-limb prosthetic technologies in the developing world: a review of literature from 1994–2010." *Prosthetics and Orthotics International* (2010)
3. Narang, Arelekatti & Winter, "The effects of prosthesis inertial properties on prosthetic knee Moment and hip energetics required to achieve able-bodied kinematics." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (2016)
4. Narang, Arelekatti & Winter, "The effects of the inertial properties of above-knee prostheses on optimal stiffness, damping, and engagement parameters of passive prosthetic knees." *ASME Journal of Biomechanical Engineering (2016)*
5. Arelekatti, Winter & Arelekatti, "Design of a fully passive prosthetic knee mechanism for transfemoral amputees in India." *ASME Journal of Mechanisms and Robotics (In Press)*