DESIGN AND DEVELOPMENT OF AN ANGULAR-VELOCITY ACTIVATED HYDRAULIC KNEE ORTHOSIS

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INTRODUCTION

Individuals with weak quadriceps due to aging, stroke, trauma or degenerative muscle disease are often at risk of knee collapse when walking or standing. As a consequence, these individuals often limit their activities, adopt compensatory movements (i.e., stabilizing their thigh with their hand, etc.), or wear a knee-ankle-foot orthosis (KAFO) that prohibits knee flexion [1]. Unfortunately, traditional KAFOs lock the knee in constant full extension throughout the gait cycle, leading to abnormal gait patterns that can lead to chronic injuries [2], decreased gait efficiency [3], higher energy expenditure [4], and early fatigue during ambulation [3]. Stance-control knee-ankle-foot orthoses (SCKAFOs) allow knee flexion during the swing phase of gait and provide knee flexion resistance during stance. Existing SCKAFO control methods require either a threshold angle (hip, knee, and/or ankle) or a threshold plantar foot pressure to change between support and free-motion modes [5-12]. These control conditions require mental effort and for most designs, may not reliably change modes for all locomotor activities. Current external control systems for SCKAFOs also add to the brace's size, cost, maintenance, and complexity.

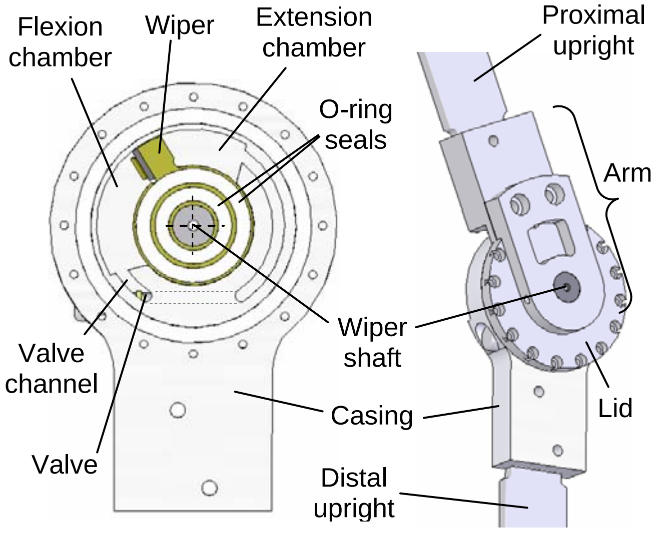
This paper presents a new approach for SCKAFO control. Based on the premise that a SCKAFO user's knee angular velocity is greater during a knee-collapse event than during walking, an angular-velocity threshold trigger can control a SCKAFO system. Since the angular-velocity-based control system does not require particular hip/knee/ankle angle or weight bearing conditions, this design will have wider applicability than current SCKAFO designs. The prototype orthotic knee joint described in this paper, referred to as the Ottawalk Speed (OWS), uses an angular-velocity activated hydraulic mechanism to achieve flexion resistance at any knee angle and is completely autonomous (no external control system).

OTTAWALK SPEED HYDRAULIC KNEE JOINT

The OWS is an angular-velocity activated orthotic knee joint, designed to allow free knee motion throughout walking, but dampen knee flexion when the knee flexes beyond a threshold angular velocity, such as during a stumble or knee collapse. The OWS therefore allows unimpeded gait while providing support by resisting unnaturally high rates of knee flexion. The OWS can be installed as a modular component on a knee orthosis or KAFO.

Structure

The main body of the joint, called the casing, contains a large pocket of uniform depth and attaches to the knee orthosis distal upright (Figure 1). A lid covers the pocket to create an enclosed chamber. A radial piston, referred to as the wiper, divides the pocket into a flexion chamber and an extension chamber. A shaft protrudes orthogonally from the wiper and extends through a hole in the lid. An arm connects the wiper shaft to the proximal upright of the knee orthosis. The two chambers are connected by a channel that contains a one-way poppet valve that is spring-biased to the open position.



(a) (b)

Figure 1: (a) First OWS with lid and arm removed; (b) First OWS prototype.

Function

Flexion of the OWS joint causes the arm, and therefore the wiper, to rotate counter-clockwise and decrease the volume of the flexion chamber. The hydraulic fluid in the flexion chamber is forced through the valve channel, past the open valve, and into the expanding extension chamber (Figure 2).

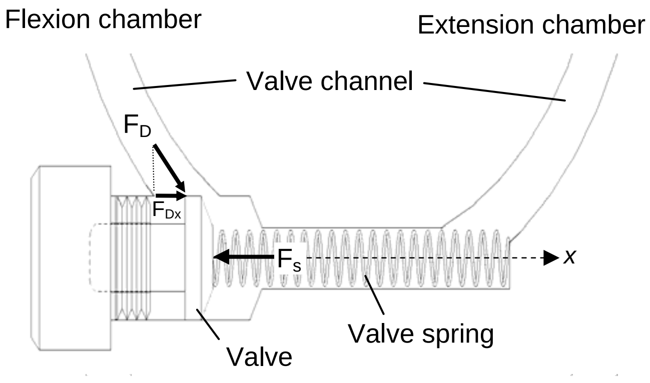


Figure 2: Valve assembly with the valve open.

In accordance with the drag equation, the drag force F_D imposed on the valve by the moving fluid is proportional to the square of the velocity of the fluid. In Figure 2, F_s is the force imposed on the valve by the biasing compression spring and F_{Dx} is the component of the drag force acting in the x-direction. When $F_s > F_{Dx}$ the valve remains open. When knee flexion angular velocity is sufficiently low, the valve remains open and knee flexion resistance is minimal.

When the joint is flexed sufficiently fast, the fluid velocity is increased such that $F_s < F_{Dx}$ and the valve closes. With the valve closed, the fluid flow is blocked and further knee flexion leads to a large pressure difference across the valve, which in turn creates a substantial resistance to knee flexion.

Substituting a spring of different stiffness or adjusting spring compression changes the spring force F_s. This allows the setting of different engagement velocity thresholds for different users. This will result in safe user locomotion with optimized function.

PROTOTYPE DEVELOPMENT AND TESTING

The first OWS prototype was machined from brass for ease of machining. Peak fluid pressure in the flexion chamber was calculated to theoretically reach 62.0 MPa, considering that a 90 kg user may generate a peak 77 Nm knee flexion moment in stair climbing [13]. The prototype joint offered very low resistance to flexion. For this prototype, the high fluid pressure in the flexion chamber caused the lid and casing to elastically deflect and allow the high pressure fluid in the flexion chamber to pass around the wiper into the low pressure extension chamber. The result was very low flexion resistance.

In an effort to reduce fluid pressure in the flexion chamber, the wiper face area of the second prototype was increased from 65.0 mm^2 to 197.5 mm^2 by lengthening the wiper. The concentric nitrile o-rings, designed to prevent fluid from leaking past the lid and shaft were replaced by a urethane u-cup seal (Hercules Bulldog Sealing Products Canada, Dorval, QC H9P1K5; Product # DSU12-0.50-12). The casing, lid and arm were machined from 7075-T651 aluminium, selected for its exceptionally high strength and low weight. The wiper was machined from 304 stainless steel, chosen for its high strength and availability. The valve channel was not initially included in the prototype during the initial testing stage in order to isolate the cause of internal leaking in the joint that lead to low flexion resistance.

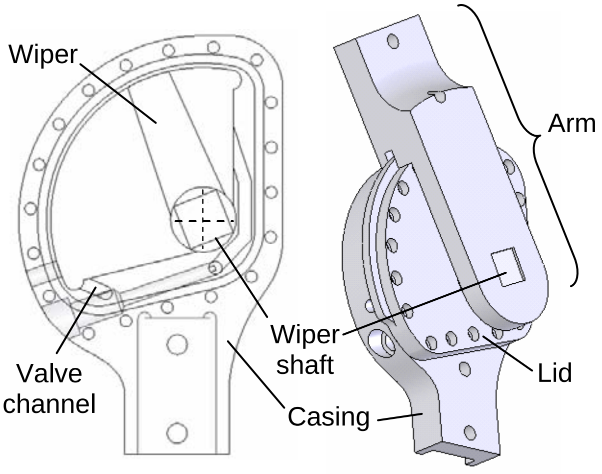
A dial test indicator (Brown & Sharpe, North Kingstown, RI, 02852; Model # 7032-2) was used to measure elastic deflection of the lid and casing bottom during joint flexion loading. With the casing of the joint clamped to a bench, the joint was flexed by hand. The lid deflected up to 0.13 mm. It was hypothesized that the casing bottom deflected by a similar amount. Deflection of the lid and casing from fluid pressure in the flexion chamber created a gap between the wiper and chamber walls that allowed sufficient fluid to pass over the wiper, thereby reducing joint flexion resistance.

After only minor improvement in a second prototype, a third prototype included a longer wiper with a face area of 292.3 mm^2 to further reduce pressure in the flexion chamber. The axis of rotation of the wiper was repositioned on the bottom right corner of the casing to allow the wiper to be lengthened by 12 mm without notably increasing the size of the joint (Figure 3). With the increased wiper face area, the peak flexion chamber pressure was calculated to reach 14.1 MPa under a 77 Nm knee flexion moment (Table 1). The casing, lid, and arm were again machined from 7075-T651 aluminium.

To increase the torsional strength of the shaft, the wiper was machined with a larger shaft diameter from 4140 steel, which was stronger than the 304 stainless steel. The third prototype generated a notably greater level of flexion resistance to the previous OWS prototypes.

Table 1: Calculated maximum chamber pressures

Prototype	**Wiper Face Area (mm^2)**	**Calculated Peak Pressure in Flexion Chamber (MPa)**
1	65.0	62.0
2	197.5	29.0
3	292.3	14.1



(a) (b)

Figure 3: (a) Third OWS prototype with lid and arm removed; (b) Third OWS prototype.

A digital pressure gauge (Setra Systems Inc., Boxborough MA 01719, Model # C206) was connected directly to a tapped hole in the flexion chamber. The distal end of the extended knee joint was oriented parallel to the ground and clamped to a bench. The proximal end of the knee joint was loaded with 78 kg (175 lbs) of body weight, approximately 40 cm from the joint's axis of rotation. The joint was loaded a total of 10 times. Joint flexion resistance was lower than desired. The peak pressure in the flexion chamber did not exceed 14 MPa throughout testing. It was hypothesized that deflection of the lid and casing under pressure was still the cause of insufficient flexion resistance.

Finite Element Analysis (COSMOS 2005; SolidWorks Corporation, Concord, MA 01742) was used to investigate various geometries of structural reinforcement to adequately stiffen the lid and casing without adding an excessive amount of weight and thickness to the joint (Figure 4). No satisfactory solution was developed by this approach.

No means of practically reducing lid and casing deflection could be devised without increasing the weight or size of the joint, therefore a squeegee-type seal, similar in concept to a windshield wiper, was designed to block the gap that formed during lid/casing deflection.

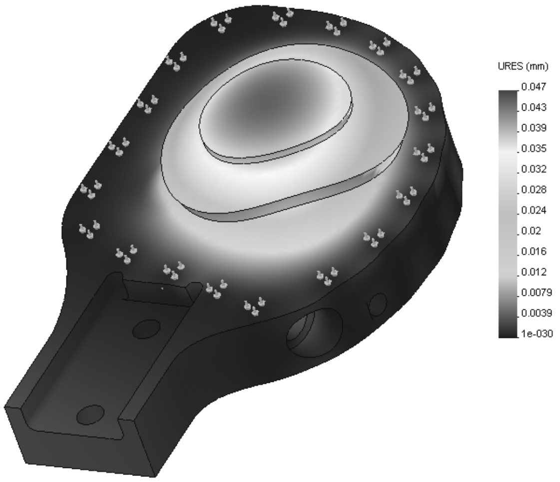


Figure 4: Finite element model of casing deflection with added reinforcement.

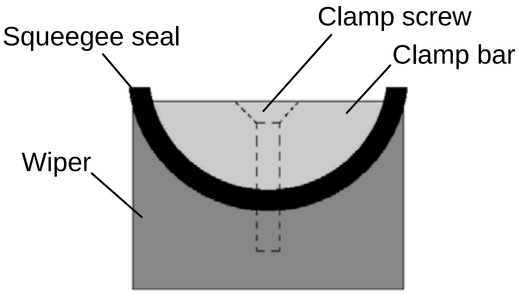


Figure 5: Cross-section drawing of the wiper with the squeegee seal.

To isolate the effectiveness of the wiper squeegee seal, the valve channel was not included in the casing during initial load tests. Elastic deflection of the lid and casing bottom during joint flexion loading was measured using the dial test indicator. The lid deflected by 0.18 mm and the casing deflected by 0.13 mm when loaded by hand, however, the OWS prototype generated a desirably high level of flexion resistance due to the effects of the squeegee seal. Further addition of the valve channel and valve to the assembly did not decrease the level of flexion resistance. This suggested that the design would be suitable for preliminary field trials.

Multiple polymer sheet materials were tested for the squeegee seal including: butyl synthetic rubber, neoprene, polyurethane, and silicone. Silicone offered the best combination of flexibility, oil resistance, and durability.

The OWS was installed unilaterally on a KAFO and is currently undergoing preliminary field tests.

CONCLUSIONS AND FUTURE WORK

The novel orthotic knee joint design outlined in this paper provides new options when prescribing an orthosis for people with quadriceps weakness. Future research will involve cyclic load testing to identify areas of wear and to ensure adequate fatigue strength, further joint load-response testing, and pilot tests with SCKAFO users. A provisional patent has been filed.

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