Preliminary Kinematic and Kinetic Evaluation of a Modular Microprocessor-Controlled Stance-Control Knee-Ankle-Foot Orthosis

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Abstract— **Stance-control knee-ankle-foot orthoses (SCKAFO) permit free knee motion during swing and knee flexion resistance during stance for individuals with knee-extensor muscle weakness. Microprocessor-controlled SCKAFO use electronic sensors and control algorithms to dictate when knee flexion resistance engages or disengages. Many SCKAFO require full leg extension to engage flexion resistance, and provide no support at other knee angles. This research presents a preliminary biomechanical evaluation of a novel local sensor-based (i.e., thigh, knee) variable knee-flexion resistance microprocessor SCKAFO (VSCKAFO) that was designed to address these limitations while maintaining stance-control functionality across various gait modes. Five able-bodied male participants were fit with the VSCKAFO and device settings were adjusted to each participant during an accommodation period. A lower body, six degree-of-freedom marker set (30 markers) was affixed to each participant. Kinematic data were collected for stand-to-sit and stair descent in a motion lab with a 10-camera Vicon system. Kinetic data were recorded for stand-to-sit with two force plates. Inertial measurement unit data were also recorded from sensors on the instrumented orthosis. It was found that the novel VSCKAFO sufficiently resisted knee flexion during weight-bearing stair descent and stand-to-sit activities. Successful biomechanical analysis with able-bodied individuals supports further testing with persons who have knee-extensor muscle weakness.**

Keywords— **gait, microprocessor, orthosis, sit-to-stand, stairs**

I. INTRODUCTION

Knee-ankle-foot orthoses (KAFO) are full leg braces for people with knee extensor weakness [1], [2]. Stance-control knee-ankle-foot orthoses (SCKAFO) permit unhindered knee motion during swing and prevent knee collapse during stance by resisting knee flexion only during the stance phase. These orthoses are prescribed to individuals with knee extensor muscle weakness and can provide more natural gait than conventional fixed-knee KAFO.

Benefits of mechanically-controlled SCKAFO include free knee rotation during swing and relatively simple control systems that do not require external power [1], [3]. However, many mechanical SCKAFO require full leg extension to engage knee-lock and offer a limited number of locking positions; therefore, individuals who are unable to fully extend their knee at every step have unreliable stance-control. This makes activities like descending stairs very difficult since the user must maintain a fully extended knee.

Some mechanical SCKAFO can enhance standing by ratcheting as they rise [4], giving support if users fall back towards the chair. However, stand-to-sit (STS) can be difficult with the knee locked and extended, making sitting awkward, and a free moving knee does not provide support. The next generation of orthotic devices benefit from microprocessor-based intelligent control using sensors.

A high-performance orthosis currently on the market is the Otto Bock C-Brace, which uses a hydraulic knee joint to provide knee flexion and extension resistances [1], [5]. The C-brace navigates activities of daily living (ADL) and walking scenarios, providing variable knee resistance at any angle. The C-brace microprocessor and sensors are built into the central fabricated orthosis making it difficult to personalize. Since sensors are located on multiple orthosis segments, orthoses such as the C-brace, can become bulky, aesthetically unappealing, and expensive.

A variable resistance microprocessor controlled SCKAFO (VSCKAFO) was recently developed to address these concerns [6]. This novel design is one of the few that use microprocessor control. Additionally, the VSCKAFO is a modular unit that localizes sensors on the thigh and knee.

The VSCKAFO uses a variable flow hydraulic valve [7], that allows for variable knee-flexion resistances. This can improve mobility across different surfaces and ADL. Localizing sensors to the knee joint and thigh makes the component lighter, and usable on existing orthoses. Being modular allows for more device personalization, and additional KAFO options. However, the performance of this novel design has yet to be quantitatively evaluated in a clinical setting.

The objective of this preliminary study was to determine whether the VSCKAFO can effectively resist knee flexion during stand-to-sit and stair descent weight-bearing movements. The VSCKAFO will allow users to descend stairs and ramps more effectively and improve user safety during slope navigation, sitting, and standing.

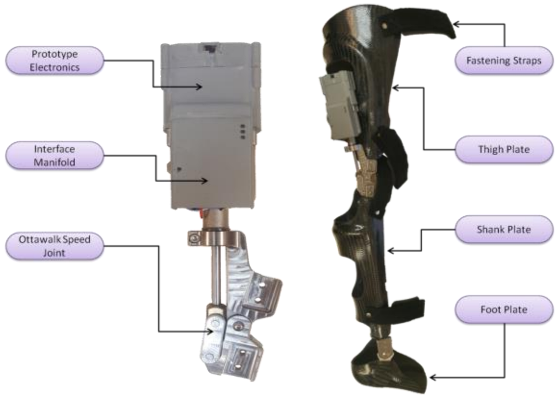

Fig. 1: VSCKAFO electrical and mechanical components.

II. METHODS

A. Equipment and Procedure

The VSCKAFO (Figure 1) uses thigh angle to control to flexion resistance, by engaging when the limb is loaded [6]. A titanium manifold was added to the design, incorporating a hydraulic piston, fluid reservoir, variable flow microprocessor-controlled valve, motor, and one-way valve that enables free extension. Electronics include a microprocessor, inertial measurement unit (IMU: accelerometer, gyroscope), Bluetooth, and knee angle sensor. The valve provides a continuous range of resistances.

Five able-bodied male participants (P01 to P05) were recruited (36.2 ± 12.7 years of age, 180.2 ± 1.9 cm height, 74.6 ± 7.3 kg weight, 90.6 ± 3.6 cm leg length). Able-bodied participants may provide larger loads on the device than users with lower limb disabilities due to a greater confidence during movement, thereby also testing the design's robustness. Participants were instructed to let the device support their body weight and were provided accommodation time to enable this behaviour.

Participants were fitted with the VSCKAFO on their right limb and device settings were adjusted to each individual during an accommodation period (stair descent resistance (SDR), stand-to-sit resistance (STSR)).

B. Data Acquisition

A lower body, six-degree-of-freedom marker set (30 markers) was affixed to each participant. Additional anatomical landmarks were defined using a digitizing wand (C-Motion Inc., Germantown, MD).

Stair descent and STS (Figure 2) were collected with a nine-camera, 3D motion capture system (Vicon Inc, Oxford, UK). Two force plates (AMTI, Watertown, MA; Bertec Corp., Columbus, OH) were used for STS. All marker data were recorded at 100Hz and ground reaction force (GRF) data were recorded at 1000Hz. VSCKAFO IMU data were recorded at 100Hz via Bluetooth. Kinetic data were only processed for STS, where GRF were available.

A step-by-step stair descent technique was used (step down with contralateral limb and then bring braced limb to the same step, allowing VSCKAFO to control knee flexion rate). Five trials, with three steps per trial, produced 15 cycles per participant. For STS, participants stood with each foot on a force plate, sat down, and then stood up without using their arms. This was repeated five times.

C. Data Processing and Analysis

Marker data were pre-processed with Vicon Nexus and then exported to Visual3D where marker and force plate data were filtered with a 4th order low-pass Butterworth filter at 10Hz before creating a seven-segment model for joint kinematics and kinetic calculations. IMU data were imported into Matlab for filtering with a 4th order low-pass Butterworth filter at 10Hz.

Peak analysis was performed in Matlab. For stair descent, minimum (KS_1) and maximum (KS_2) knee angles, maximum knee flexion angular velocity (KVS_1), and maximum knee extension angular velocity (KVS_2) were computed. For STS, maximum peak knee angular velocity (KVsts), maximum peak knee moment (KMsts), and minimum peak knee power (KPsts) were calculated.

Stair descent parameters and peak values were compared with able-bodied literature [8] (i.e., normal data set). Participants in the literature descended step-over-step rather than bringing the contralateral limb to the same step.

Fig. 2: Stair descent and stand-to-sit activities.

III. RESULTS

Figure 3 shows the knee angle and angular velocity for 15 stair cycles for P02 and normal stair descent dataset. The braced knee's angle ROM for stair descent was 4.45% (SD =

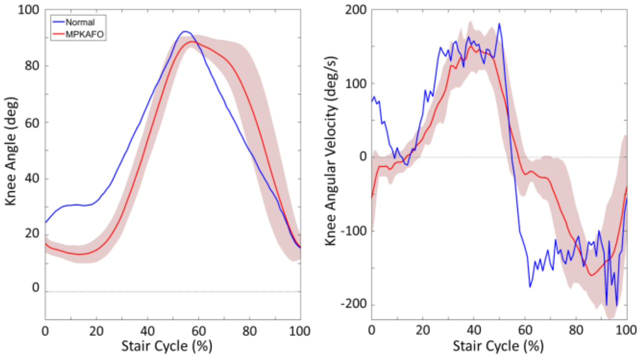

Fig. 3: Knee angle (deg) and angular velocity (deg/s) for participant 2 and the normal comparator dataset [8] for stair descent.

6.73%) less than knee angle ROM for the normal stair descent dataset. Stair descent knee angle ROM decreased by 8.42%, 1.16%, 11.49%, and 6.73% for P01, P02, P04, and P05 respectively. Stair descent knee angle ROM increased by 5.55% for P03.

Stair descent peaks are shown in Table 1. P05 had the lowest average minimum knee angle, while P04 had the greatest average maximum knee angle. The average minimum angle was 11.06 deg, which is slightly less than the minimum angle during normal stair descent. The average maximum knee angle was 84.45 deg, which is less than the normal walking maximum angle.

The average maximum flexion velocity (KVS_1) was 137.53 deg/s, which was less than normal. P02 had noticeably greater flexion velocity than other participants of 178.62 deg/s, which was similar to normal stair descent. The average maximum extension velocity (KVS_2) was 215.31 deg/s, which was similar to normal. P04 had a slightly lower extension velocity than other participants.

Table 2 shows the maximum knee angular velocity, knee moment, and minimum knee power for the braced limb during stand-to-sit. The average knee angular velocity was 114.19 deg/s, with P05 having the noticeably lower angular velocity at 96.73 deg/s (SD=8.2).

Average maximum knee moment for the participants was 0.72 Nm/kg, and average minimum knee power was 1.14 W/kg. P05 had noticeably different results, having a mean knee moment of 1.16 (SD=0.11) Nm/kg, and mean power of 1.63 (SD=0.27) W/kg.

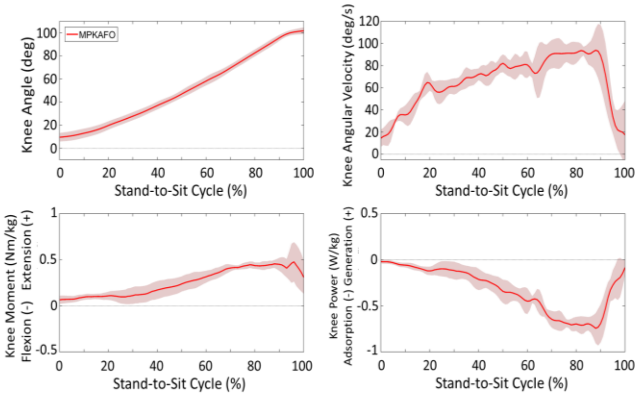

Fig. 4: Knee angle (deg) and angular velocity (deg/s) for participant 2 for stand-to-sit.

Table 1: Stair descent peak values and timing for knee angle (KS_1 and KS_2) and angular velocity (KVS_1 and KVS_2)

	KS_1 (deg)	**% gait cycle**	**KS_2 (deg)**	**% gait cycle**
P01	13.8±14.2	4.2±4.7	84.1±2.4	66.1±6.1
P02	14.3±6.4	10.3±7.0	90.2±1.4	56.3±7.1
P03	3.7±2.6	11.2±6.5	84.8±3.4	72.8±8.2
P04	20.9±2.9	4.9±4.8	88.9±2.7	64.0±6.5
P05	2.7±2.8	5.8±7.2	74.3±15.2	71.8±6.8
Normal	15.4	0.0	92.2	-55.0
	KVS_1 (deg/s)	**% gait cycle**	**KVS_2 (deg/s)**	**% gait cycle**
P01	124.5± 23.4	49.3± 10.3	-240.6±35.9	87.3± 4.2
P02	178.6± 28.7	40.8± 7.5	-209.9±33.3	85.9± 7.5
P03	148.9± 20.5	54.5± 10.3	-232.3±28.5	90.3± 3.9
P04	120.6± 20.2	52.0± 6.9	-175.3±33.6	86.0± 8.6
P05	115.1± 41.6	49.5± 6.5	-218.5±37.5	90.0± 6.2
Normal	181.2	-50.0	-200.9	-96.0

Table 2: Stand-to-sit peak analysis for knee angular velocity, moment, and power

	KV_{STS} (deg/s)	**% sit cycle**	**KM_{STS} (Nm/kg)**	**% sit cycle**
P01	125.53±10.2	66.2±23.7	0.58±0.07	88.8±2.6
P02	110.95±14.1	78.4±12.4	0.59±0.14	89.8±7.3
P03	120.01±11.1	39.50±4.1	0.54±0.06	59.50±7.0
P04	117.72±31.0	86.2±6.6	0.74±0.14	88.00±4.0
P05	96.73±8.2	37.67±9.5	1.16±0.11	61.83±9.8

	KP_{STS} (W/kg)	**% sit cycle**
P01	-1.06±0.12	80.6±9.0
P02	-0.84±0.15	82.8±7.3
P03	-1.02±0.2	60.8±14.1
P04	-1.17±0.37	86.0±3.7
P05	-1.63±0.27	55.8±12.9

IV. DISCUSSION

For stair descent, VSCKAFO maximum knee flexion was similar to normal [8]. Since knee flexion approached 90°, the VSCKAFO would also work for step-over-step descent. Often, KAFO users are unable descend stairs because their locked knee does not allow the required toe clearance [9]. Being able to achieve similar ranges of motion to normal while resisting flexion is a beneficial feature of the VSCKAFO. Minimum knee angle was slightly lower than normal, likely due to the difference between the step-by-step data in this study and the step-over-step normal data [8] (i.e., leg straightens with step-by-step but not with step-over-step).

For knee velocity during stair descent, all participants except P04 had similar or greater extension velocities than normal. P04 may have been less confident during descent, thereby walking slower.

Most participants had slower flexion velocity than normal, due to VSCKAFO flexion resistance settings. Faster flexion could be achieved by lowering the resistance setting or keeping settings the same for heavier users. The exception was P02 who, despite having a yield setting similar to the other participants and being lighter, had a flexion velocity most similar to normal stair descent. Since P02 had more experience in the device, they may have loaded the device to a greater degree during descent.

As with stair descent, the maximum velocity for stand-to-sit depends on the resistance setting, participant weight, and participant reliance on the VSCKAFO. P01 had the lowest resistance setting and the greatest angular velocity. P05 had the lowest angular velocity during sitting, and the highest resistance, while being the heaviest. Therefore, the custom resistance setting appropriately controlled knee angular velocity during sitting.

However, considering P05 was the heaviest and had an equivalent yield setting to participants 3 and 4, participant 5 used a different sitting strategy to have the slowest angular velocity. Some differences in velocities can be expected based on how much the person uses their contralateral limb and varies their upper body posture. This different strategy is further demonstrated by P05's greater peak moment and peak power per kilogram than the other participants.

Different sitting strategies could depend on different muscle capabilities, demonstrating the benefit of having customizable resistance. In this study, chosen resistance settings differed despite participants having similar weights. Participant 5 was 8kg heavier than P03, but they selected the same resistance setting. The need for customizability increases even further with differing levels of muscle control in those with movement disorders.

Peak velocity, moment, and power occurred near the end of sitting, when knee angle was greatest. This was expected since the moment increases as the moment arm increases (horizontal distance from knee to centre of mass). Despite the changing moment throughout sitting, setting one resistance was acceptable for all participants.

V. CONCLUSION

Using a novel, lightweight, modular MPKAFO, participants were able to descend stairs and perform stand-to-sit at a customized resistance. The results of this preliminary study demonstrated that the VSCKAFO resisted knee flexion during weight-bearing for stair descent and stand-to-sit. Kinematic analysis showed that stair descent with the device was similar to normal stair descent, achieving the same range of motion while also resisting descent. Customizable resistance appeared to benefit different sitting strategies, which will be important for accommodating varying muscle strengths for people with lower limb weakness. Next phase research will involve people with knee extensor weakness to understand the best approach for configuring VSCKAFO settings for stair descent and sitting.

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