Examination of Knee Joint Moments on the Function of Knee-Ankle-Foot Orthoses During Walking

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The goal of this study was to investigate clinically relevant biomechanical conditions relating to the setup and alignment of knee-ankle-foot orthoses and the influence of these conditions on knee extension moments and orthotic stance control during gait. Knee moments were collected using an instrumented gait laboratory and concurrently a load transducer embedded at the knee-ankle-foot orthosis knee joint of four individuals with poliomyelitis. We found that knee extension moments were not typically produced in late stance-phase of gait. Adding a dorsiflexion stop at the orthotic ankle significantly decreased the knee flexion moments in late stance-phase, while slightly flexing the knee in stance-phase had a variable effect. The findings suggest that where users of orthoses have problems initiating swing-phase flexion with stance control orthoses, an ankle dorsiflexion stop may be used to enhance function. Furthermore, the use of stance control knee joints that lock while under flexion may contribute to more inconsistent unlocking of the stance control orthosis during gait.

Keywords: gait, lower limb, stance phase control, rehabilitation, stance control orthosis

An estimated 1.8% of the population requires some form of orthotic treatment. 1 In more severe cases of impairment and the presence of quadriceps muscle weakness, knee-ankle-foot orthoses (KAFOs) are prescribed to assist joint stability. 2 KAFOs constrain the motion at the knee joint in a fully extended position during weight bearing, thus assisting or replacing diminished muscle function. 2,3 However, with standard KAFOs this immobilization of the knee restricts flexion during the swing-phase of gait. To compensate for this imposed constraint KAFO users typically adopt abnormal gait patterns, including circumduction, hip hiking and/or vaulting and excessive trunk movements. These gait compensations, along with increased energy expenditure levels owing to locked knee gait 4 account for typically high rates of KAFO disuse that are in excess of 60% in favor of alternate assistive devices such as wheelchairs. 5

Stance control orthoses are KAFOs that function to restrict knee flexion during stance-phase, but unlike standard KAFOs allow the knee to flex during the swing-phase. 6 This is termed stance control or stance-phase control. It is achieved by activating a lock or brake in the stance control orthosis during the weight bearing part of the gait cycle (ie, stance-phase) and deactivating it during nonweight bearing (ie, swing-phase). Consequently, compared with traditional KAFOs with continuously locked knee joints, stance control orthoses have been shown to increase walking speed, 7–9 increase efficiency, 5,10,11 reduce compensatory gait deviations, 12 and decrease associated secondary health complications such as back problems and soft tissue injuries. 9

To facilitate stance-phase control, stance control orthoses are designed to react to commonly occurring kinematic and/or kinetic features of gait. In particular, with the exception of microprocessor-based stance control orthoses such as the SensorWalk from Otto Bock, which utilizes a battery-powered electromechanical clutch, most stance control orthoses are unlocked in the presence of an external knee extension moment (or elimination of flexion moment) in the latter part of stance-phase. 13,14 While the need for an extension moment to deactivate locking is an inherent mechanical attribute of most passive (non-powered) mechanisms, it does serve a useful function in terms of user safety, by ensuring that the lock does not release while the stance control orthoses is providing stance-phase support. 14 Evidence is emerging, however, to suggest that the presence of external knee extension moments in stance-phase of KAFO gait may not be as pronounced as originally determined using traditional gait laboratory assessments. 8,15,16 Recent studies utilizing load transducers in KAFOs suggest that gait laboratory measurements of external knee extension moments in stance-phase are largely overestimated, 17 and that these
moments are actually either considerably diminished in stance-phase, or entirely absent in KAFO gait. This potential absence of knee extension moments is further evidenced in clinical studies evaluating stance control orthosis function, whereby stance control orthosis users were reported to require increased mental and physical effort to release stance control orthosis locks. Stance control orthosis function that is unreliable or excessively demanding on the user is likely to lead to poor clinical outcomes and abandonment of the assistive device. For this reason, greater insight is needed into the factors and clinically relevant conditions that influence the production of external knee extension moments.

There exist at least two clinically relevant KAFO conditions that effect the production of stance-phase knee extension moments. The first condition relates to the type of ankle joint used in a KAFO. KAFO ankles can either be articulating to allow ankle motion, or fixed to constrain ankle dorsi/plantarflexion. Permitting ankle movement is functionally beneficial for the KAFO user as it enhances forward progression and overall function. However, a fixed ankle, or alternatively one that restricts dorsiflexion, is more likely to create or enhance knee extension moments in late stance-phase, a desired effect for more reliable stance control orthosis function. The second condition relates to knee joint alignment, specified as the angle between the shank and thigh portions of the KAFO. Due to commonly occurring physical conditions associated with KAFO users, such as knee flexion contractures and/or impaired hip function inhibiting swing-phase control and full-knee extension, a stance control orthosis knee joint may be locked in a slightly flexed position during the stance-phase of gait. When this happens knee flexion moments increase in midstance, however, the effect on external knee extension moments is unclear.

The overall goal of this work was to examine the effects of clinically relevant KAFO setup and alignment conditions on the control of stance control orthoses. The particular aims were to determine: 1) whether external extension moments at the orthotic knee joint are present in the latter part of stance-phase of KAFO gait, 2) whether these can be increased by adding a dorsiflexion stop to a freely articulating KAFO ankle joint, 3) whether a fully extended knee joint will produce higher knee extension moments when compared with one that is slightly flexed, and 4) whether the differences in the external extension moments found for the abovementioned conditions are an artifact of differences in walking speeds. This last point is important in determining whether changes observed in extension moments are due to the biomechanical changes imposed by a specific knee alignment or ankle setup condition, or indirectly by changes in walking speeds that stem from the imposed changes in KAFO conditions.

### Methods

#### Instrumentation

Knee moments were measured at the lateral knee joint axis of the KAFO using a 6 degrees-of-freedom load transducer (MCW-6-XX 1000, Advanced Mechanical Technology Inc., USA) and the CRONOS LPL-2 DIO 8-analog channel amplifier/data acquisition system with imc Devices 2.5 software (imc DataWorks, USA). Accuracy of the instrument as specified by the manufacturer is ± 0.2 of full scale. Data were sampled at 1KHz. Custom-made attachments were used to rigidly attach the load transducer to the KAFO in place of the lateral orthotic knee joint (Figure 1). Moreover, these attachments were designed to allow the sagittal plane alignment between

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**Figure 1** — Sagittal (left) and frontal (middle) view of a KAFO instrumented with the load transducer. A participant wearing the instrumented KAFO, as well as, reflective spherical markers used for the gait laboratory measurements (right). Details of the attachment of the load cell including setscrews to prevent motion in the sagittal plane (bottom).
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the thigh and shank uprights to be adjusted from 0 (straight) to 20 degrees of flexion. Subject feedback and examination of the setup by a certified orthotist (JK) were used to ascertain that the instrumented KAFO setup was functionally and structurally comparable to the original KAFO setup.

Spatiotemporal, kinematic and kinetic gait parameters were concurrently captured using the VICON MX system (Vicon Peak Inc., UK) which was synchronized with the load transducer system using a trigger. VICON MX system was comprised of 7 infrared cameras sampling at 120 Hz to track motions and two forceplates (Bertec 4060, Bertec Corp, USA) located midway along a 10-m walkway recording ground reaction forces at 1000 Hz. Reflective markers were attached to the participant. Reflective markers were placed on the shoes in the proximity of the heads of the first and fifth metatarsals, midpoint between the base of the first and fifth metatarsals, posterior calcaneus, and lateral and medial ankle malleoli. Markers were placed on the anterior and lateral midshank, lateral and medial femoral condyles, and lower anterior and lateral thigh. On the braced limb the malleoli markers were placed at the hinge of the mechanical ankle joint and a knee marker was placed on the medial hinge of the mechanical brace knee joint. Two knee markers were placed on the medial and lateral aspects of the load transducer aligned with the knee axis and additional markers placed axially on the top and bottom were used to define load cell orientation (Figure 1).

Participants and Preparation

The study involved a convenience sample of four adults diagnosed with poliomyelitis and post poliomyelitis. The characteristics of the participants are presented in Table 1. Participants were identified by a certified orthotist. All of the participants regularly used KAFOs for at least 2 years before the study and were good community ambulators. All participants presented with unilateral muscle weakness with normal muscle strength levels and function of their contralateral limbs. Participation was not restricted on the basis of muscle strength, however, knee flexion contracture on the braced limb was restricted to 15 degrees or less, as this is a clear contraindication for stance control orthosis prescription.

Each participant underwent a clinical assessment by a certified orthotist to determine physical characteristics including height, weight, joint ranges of motions and muscle strength using the manual muscle strength test. For each participant, a new KAFO was constructed using modular components (Otto Bock GmbH, Germany) to allow for substitution of the lateral orthotic knee joint for the load transducer. A double action ankle joint attached to stainless steel split stirrups was used (model 17B66 = 20). This allowed for adjustable plantar and dorsiflexion range of motion; in this way, the joint could be setup either as a free hinge or with a dorsiflexion stop. Slight plantar flexion resistance was provided using a spring. Stainless steel lock ring knee joints (model 17B42 = 20) were used at the knee and stainless steel side bars were used in all cases. Once the braces were fabricated, participants were given a minimum 2-week period of acclimation before testing. Approval was received from the institution’s research ethics board and informed consent from the participants.

Procedure

Testing was performed during a single session. To assess the effect of ankle setup on knee extension moments, the ankle was configured as either a freely moving ankle joint (Ankle Free) or with a dorsiflexion stop (Ankle Stop). To assess the effect of knee conditions, the knee was either setup as a straight knee (Knee Straight) or a flexed knee (Knee Flexed). Thus testing was done for the following combinations of conditions, and in the specified order, including Knee Straight & Ankle Stop, Knee Straight & Ankle Free, Knee Flexed & Ankle Free, and Knee Flexed & Ankle Stop. The Knee Straight condition reflects the prescribed alignment as determined by the certified orthotist. The actual alignments (ie, angle at the knee) are provided in Table 1. For the Knee Flexed condition, between 9 and 10 degrees of knee flexion was added. In the Ankle Stop condition, the stop was adjusted to

Table 1  Subject characteristics including joint alignment and muscle function. Muscle strength based on manual muscle test.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Weight (kg)</th>
<th>Knee flexion contracture (°)</th>
<th>Alignment of the KAFO knee joint (°)*</th>
<th>Affected limb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ankle: dorsiflexion / plantar flexion</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>42</td>
<td>91</td>
<td>15</td>
<td>6</td>
<td>1/1</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>27</td>
<td>66</td>
<td>10</td>
<td>8</td>
<td>0/0</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>34</td>
<td>87</td>
<td>5</td>
<td>0</td>
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</tr>
<tr>
<td>4</td>
<td>M</td>
<td>29</td>
<td>60</td>
<td>5</td>
<td>0</td>
<td>0/0</td>
</tr>
</tbody>
</table>

*Angle measured between the lower (shank) and upper (thigh) uprights using a manual goniometer.
provide as much dorsiflexion resistance in late stance-phase as was comfortably tolerated by the subject. Once instrumented, participants were instructed to walk at their comfortable, self-selected walking speed. At least three complete trials per condition were captured and used in the analysis. For a complete trial it was required that no markers were obstructed and that forceplate data were acquired.

Data Analysis

Programs were written in Matlab (The MathWorks Inc., USA) to downsample and time-normalize load transducer data. The sagittal plane knee joint moments were then normalized to subject’s body weight. The normalized external knee extension moments were extracted by taking the maxima of the sagittal knee joint moment found between 40% gait cycle and toe-off (Figure 2). To generate spatiotemporal (walking speeds) and kinematic (ankle joint angles) parameters, gait laboratory data were processed in Vicon Workstation and BodyBuilder software (Vicon Peak Inc., UK) using conventional methods.17,24

To examine the effects of the KAFO setup/alignment conditions (Ankle Stop vs. Ankle Free and Knee Straight vs. Knee Flexed) on knee joint moments, a repeated measures analysis of variance using SAS software was performed controlling for random subject effects. Effects with a $P$-value of less than 0.05 were considered significant.

Results

External knee extension moments were not generally produced in KAFO gait (Figures 2 and 3). Only one subject (subject 4) for one condition (Knee Straight & Ankle Stop) produced an external knee extension moment in stance-phase. None of the other participants were able to consistently produce an extension moment, regardless of the ankle setup or knee alignment that was applied, although subject 3 did on occasion get close under the Knee Straight & Ankle Stop condition (Figure 3).

Adding a dorsiflexion stop at the KAFO ankle increased the external knee extension moment ($P < .0001$) (Figure 4). In all cases the Ankle Stop condition resulted in a higher mean external knee extension moment over the Ankle Free condition, although the extent to which this occurred was highly variable across subjects. Based on the gait laboratory data, adding a dorsiflexion stop at the ankle decreased stance-phase dorsiflexion by 1–5 degrees across all subjects, resulting in average increases of dorsiflexion ankle moments of 0.13 (range 0.02–0.22) N·m/kg.

The knee condition (Knee Straight vs. Knee Flexed) had a variable effect on external knee extension moments. While on average external knee extension moments were higher for the Knee Flexed versus Knee Straight condition, this difference did not reach statistical significance ($P = .074$) (Figure 4). For participants 1 and 2 external knee extension moments were clearly higher for the Knee Flexed condition when compared with Knee Straight condition, while for participants 3 and 4 results varied depending on the ankle condition (Figure 3). Corresponding angles between the thigh and shank portions of the KAFO ranged from 0 to 8 degrees for the Knee Straight condition and 9–17 degrees for the Knee Flexed condition across the four participants (Table 1).

No differences in walking speeds were found between conditions. Comparing the Ankle Stop to Ankle Free conditions, gait velocities were 0.78 (± 1 SD of $\pm 0.05$ were considered significant.

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**Figure 2** — Normalized external knee joint moments averaged for the four participants for the Knee Straight & Ankle Stop condition obtained using the load transducer. Errors bars show ±1 standard deviation. Data for able-bodied individuals are also shown, reproduced from Seroussi et al.25 The peak external knee extension moment in late stance-phase indicated. Positive values indicate external extension moments. $M_{ext} =$ normalized external knee extension moment.
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0.16) m/s and 0.79 (± 1 SD of 0.16) m/s, respectively (P = .81). Comparing the Knee Straight and Knee Flexed conditions, gait velocities were 0.80 (± 1 SD of 0.15) m/s and 0.77 (± 1 SD of 0.17) m/s, respectively (P = .38).

Discussion

As a treatment, stance control orthoses can offer individuals with lower-limb impairments numerous functional improvements over more traditional KAFOs with locked knee joints. This, however, assumes that the stance control orthosis can be operated in a safe, reliable, and efficient manner; a key element of this is the user’s ability to produce an external knee extension moment in stance-phase. The goal of this study was to investigate clinically relevant conditions that influence the production of stance-phase knee extension moments in KAFO gait, so as to ultimately help inform and improve clinical prescription practices, as well as the design and development of more effective stance control orthoses.

One way an orthotist is able to influence knee moments in the stance-phase is by restricting motion at the KAFO ankle joint. The provision of a dorsiflexion ankle stop had a positive effect on the production of a knee extension moment in latter stance-phase when compared with a free ankle. In the Ankle Stop condition, restricting ankle motion resulted in a more anterior load on the foot and therefore a ground reaction force vector that produced a greater knee extension moment. This finding is important, as it provides evidence about the type of ankle setup that an orthotist should consider prescribing in the event that a patient is not able to reliably operate a stance control orthosis. Particularly, consideration should be given to the use of ankle joints with an adjustable dorsiflexion stop.

While the Ankle Stop condition did significantly increase the external knee extension moments in stance-phase, a positive external knee extension moment was only produced by one of the four participants. For the other three participants external knee flexion moments persisted throughout stance-phase, even with full ankle

Figure 3 — Normalized external knee extension moments for the four testing conditions. Average of 3 trials and ±1 standard deviation shown by error bars. Positive values indicate external extension moments.

Figure 4 — Differences of the normalized external knee extension moments for KAFO conditions. Mean difference and 95% confidence limits shown by error bars.
dorsiflexion resistance. This suggests that an ankle dorsiflexion stop is only partially effective in promoting knee extension moments in stance control orthoses. As such, it may be necessary for orthotists to consider other ways in which to setup a KAFO to enhance these moments, such as by adding an extension assist at the knee joint. Alternatively, greater focus may need to be placed on the development of stance control orthoses that do not rely on a knee extension moment to unlock.

Sagittal plane alignment of a KAFO has a well established effect on knee joint moments. In midstance, flexion at the knee brings the knee joint axis forward of the ground reaction force vector, thus increasing the flexion moment at the knee joint. However, the effect of a flexed knee on extension knee joint moments appears to be less obvious. As seen in Figures 3 and 4, the Knee Flexed condition produced variable results; for some of the participants extension knee moments increased under the Knee Flexed condition while for others they decreased. In certain stance control orthoses such as the Horton SCOKJ or Becker E-knee which are designed to lock under different amounts of knee flexion, the stance-phase knee angles are likely to change from step to step, in turn resulting in more variability in stance-phase extension knee moments. Given that, when compared with able-bodied gait (Figure 2) KAFO knee extension moments produced in late stance-phase are at best quite small, this additional variability is likely to adversely affect the reliability of stance control orthosis unlocking during gait.

This study focused on examining factors relating to KAFO setup and alignment. However, it is important to note that there are other factors to consider. One important contraindication for stance control orthosis prescription is knee flexion contracture that is greater than 5–15 degrees, depending on the specific stance control orthosis design. An obvious reason for this contraindication is that excessive knee flexion contractures would prevent stance control orthosis users from having an adequately extended leg in stance-phase. This is problematic not only because it results in an unnatural posture and crouched gait, but as seen from the results of this study, it is also likely to inhibit the production of an extension knee moment. In particular subject 4 with a smaller knee flexion of 5 degrees produced an extension moment while subjects 1 and 2 with larger contractures did not.

Another important indication/contraindication for stance control orthosis prescription is a patient’s hip muscle strength. Although it was not a formal goal of this study to assess this aspect, a knee extension moment in late stance-phase does appear to be enhanced with increased hip extensor strength. Particularly, referring to Table 1 and Figure 3, subject 4 with hip extensor strength of 4 was the only one of the group able to produce an extension knee moment. This coincides with other findings. In that study the two subjects with low levels of impairment (hip extensor strength of 4 or more) were able to generate a knee extension moment in late stance-phase to operate a prototype stance control orthosis, while the subject with hip extensor strength of 3 required additional alterations to his KAFO setup to unlock the knee. It also coincides with a study by Irby et al. that found that the group of stance control orthosis users with an aggregate lower hip extensor strength (1.5 versus 3.0) produced lower knee extension moments at toe-off. Biomechanically, these findings appear logical, since generating a larger hip extensor moment will increase the external knee extension moment. Moreover, weak hip extensors result in postural deviations such as trunk lean, and increased knee flexion, which can affect the Center of Mass and ground reaction forces, and as a result the knee moments in stance-phase. Hence, hip extensor function appears to be an important factor that needs to be considered in the prescription of stance control orthosis.

As part of future work, a more in depth examination of factors such as hip muscle strength and knee flexion contractures is needed to allow clinicians to better determine which patients are most likely to benefit from stance control orthoses. Future work should also be extended to real-life environments and include larger sample sizes, a limitation associated with this study that is largely attributed to the instrumentation that was used. To accept the load transducer, it was necessary to make a new KAFO for each participant. This is a costly and resource intensive process, and therefore may be a limiting factor in testing large sample sizes. However, where clinics consistently use modular KAFO systems such as the one used here, a relatively simple substitution of the load transducer is possible.

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References


