Knee Biomechanics of Alternate Stair Ambulation Patterns

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ABSTRACT

REID S. M., S. K. LYNN, R. P. MUSSELMAN, and P. A. COSTIGAN. Knee Biomechanics of Alternate Stair Ambulation Patterns. Med. Sci. Sports Exerc., Vol. 39, No. 11, pp. 2005–2011, 2007. Purpose: This study compared the kinematics and kinetics of the knee joint during traditional step-over-step (SOS) and compensatory step-by-step lead-leg (SBSL) and trail-leg (SBST) stair ambulation patterns. Methods: Seventeen (M:9) healthy adults completed five trials of ascent and descent using three different stepping patterns: 1) SBSL, 2) SBST, and 3) SOS. Kinematics and kinetics were collected with an optoelectronic motion-tracking system and a force plate embedded into a four-step staircase. An inverse-dynamics link-segment model (QGAIT system) was used to calculate the net joint kinetics. Results: During stair ascent, different peak anteroposterior (AP) forces were observed across all three stepping patterns (SOS > SBSL > SBST, P < 0.05). During ascent, the flexion moments of SOS (0.96 Nm/kg) and SBSL (0.97 Nm/kg) patterns were similar and much larger than the SBST moments (0.14 Nm/kg). In the descent conditions, the initial AP peak force for SOS was larger than that of SBSL and SBST. However, the second peak force for SOS (4.92 N) and SBST (4.68 N) were larger than SBSL (1.57 N). During descent, the initial peak flexion moment for the SOS pattern was larger than SBSL and SBST, whereas during the second peak, SOS (1.05 Nm/kg) and SBST (1.11 Nm/kg) were no different and larger than SBSL (0.18 Nm/kg). Conclusion: Overall, SBSL during ascent and SBST during descent had the highest loads. These results increase our understanding of alternative stepping patterns and have important clinical (reduction of loading on injured/diseased leg) and rehabilitation implications. Key Words: STEP-BY-STEP, STEP-OVER-STEP, STAIRS, LOWER-LIMB KINETICS

Because stair climbing is a common activity of daily living, the ability to do it efficiently is important to an individual’s quality of life (16). More demanding than level walking, stair ambulation is performed with ease by healthy individuals; however, it is more difficult to perform for those with decrements in motor function, balance problems, or reduced lower-limb function. The difficulty with stair climbing is attributable to increased muscular demands, which are reflected in larger forces (4), angles (1), powers (14,19), moments (4,12,14), and ranges of motion (ROM) (16), and these increased demands occur consistently at the knee joint.

Generally, healthy individuals use a traditional step-over-step (SOS) gait pattern during stair ambulation; however, patients, older adults, and disabled populations may be forced to adjust their stair gait pattern because of decrements in muscular strength (8,15,24), decreases in proprioceptive acuity (8), and altered balance mechanisms (15,24) associated with age and disease (18,22). Therefore, those populations with decrements in motor function often adopt alternate gait patterns, such as increased handrail use, sideways motion, or a step-by-step (SBS) pattern (placing both feet on the same step before ascending or descending) that deviate from the traditional SOS gait pattern (21,22). These deviations in stair gait patterns result in higher energy costs, lower efficiency, and an increased risk of falling, particularly during stair descent (21–23) and SBS gait pattern.

The majority of stair biomechanics research has focused on stair ambulation as a tool for defining performance limits during rehabilitation (14), to assess functional abilities (3), or after surgical interventions such as knee replacements (2,7,11). At present, no literature provides an in-depth description of the biomechanics of alternate stair ambulation gait patterns. Much of the functional impairment during
stair negotiation is directly related to the knee (1,4,14, 19,20) and is manifest in healthy people as they age and in those who live with knee osteoarthritis. Exploration of the effects of alternate stair ambulation patterns on the knee joint biomechanics is warranted to enhance gait rehabilitation strategies and for comparison of knee mechanics of different strategies. In evaluating stair climbing ability, it is important to consider the method used to negotiate the stairs. What was the stepping speed? Was a handrail used? Was the pattern the typical SOS pattern or the modified SBS pattern? These different stepping methods alter the mechanics of stair stepping, and the way the mechanics are altered must be known if we want to understand the additional compensations that populations, such as older adults or those with knee osteoarthritis, use in negotiating stairs. We need to be able to discern whether differences from “normal” stepping are attributable solely to changes in the ambulation pattern, or whether it is possible that additional compensations are at work.

METHODS
Seventeen (nine male and eight female) normal, healthy adults without history or complaint of chronic pain, major injury, or surgery to the lower limbs or back participated in the study. Participants were 18–35 yr old (mean = 23.71, SD = 2.37), and mean height and mass were 185.1 cm (SD 11.7) and 82.1 kg (SD 14.3), respectively. The university research ethics board approved the procedures, and all participants provided informed written consent.

Motion was tracked with an Optotrac 3020 three-dimensional tracking system (Northern, Digital, Waterloo, Canada) while a force plate (AMTI, Newton, MA) measured the ground-reaction forces. The stairs were of standard dimensions, with each step being 15 cm high and 26 cm deep, with a tread of 56 cm. The force plate (shaded areas) was not attached to the staircase; it was possible for subjects to step onto the stair beside the force plate while the test leg stepped onto the force plate.

Radiographs. Before data collection, each participant had three standardized radiographs taken of their test leg (3). The radiographs included a frontal view of the knee and hip and a sagittal view of the knee. During the procedure, the participants stood on a rotatable platform in a test frame behind two accurately spaced Plexiglas sheets. The Plexiglas sheets in front of the lower limb contained lead beads embedded at precise locations. The lead beads were imaged along with the limb; because the configuration of the beads was known, image magnification and distortion could be corrected. The participant was positioned so that the lateral view approximated the knee flexion plane, and, by rotating the turntable 90° so the participant need not move, the frontal view was orthogonal to the lateral view.

FIGURE 1—Schematic drawing of the four-step staircase, with the force plate mounted on concrete blocks to form the second step. The stairs were of standard dimensions, with each step being 15 cm high and 26 cm deep, with a tread of 56 cm. The force plate (shaded areas) was not attached to the staircase; it was possible for subjects to step onto the stair beside the force plate while the test leg stepped onto the force plate.

Virtual markers. All radiographs were taken with lead beads taped to the lateral aspect of the leg where the motion collection markers would be placed later. These beads were imaged along with the knee’s internal structures and were attached at the greater trochanter, lateral femoral epicondyle, and the head of the fibula. Distances between the imaged lead beads and specific bone landmarks were measured and corrected using calibration information derived from the radiograph procedure. This allowed specific internal bone landmarks to be located with respect to the local limb coordinate systems developed from the surface markers. The specific internal landmarks were the centre of the femoral head, the midpoint of the distal femur, the midpoint of the proximal tibia, and the midpoint of the ankle malleoli.

Gait data. During the stair ascent and descent trials, the participants had four infrared markers (IRED) affixed to the lateral aspect of their test leg at the same locations as those of the lead beads used in the x-rays (4). In addition, a single IRED was attached to a forward-projecting probe strapped securely to the midtibia, and another was strapped to the upper tibia just below the tubercle (4).

After marker preparation, each participant completed five trials of ascent and descent using three different stepping patterns: 1) SBS, leading with the test leg (lead leg) (SBSSL), with placement of both feet on the same step, examining the leading leg; 2) SBS, leading with the non-test leg (trail leg)
The Queen’s Gait Analysis Three-Dimensional (QGAIT) system protocol, described and validated previously (5,6,9), was used to process both the kinematic and kinetic data. QGAIT used information from the standardized radiographs, participant-specific anthropometrics, and kinematic and kinetic data to calculate three-dimensional angles, net forces, and net reaction moments at the knee. The floating axis method (9) calculated three-dimensional knee angles, and a standard link-segment model calculated the three-dimensional net forces and net reaction moments at the knee. The forces and moments were defined using the right-hand rule in the tibia local coordinate system. The computed forces and moments are the net external forces and moments, not their internal counterparts. For example, a positive flexion moment represents a net external flexor moment at the knee, which is resisted by the knee extensors.

Data analysis. The QGAIT system calculated three-dimensional knee angles, net forces, and net moments at the knee, as well as standard time–distance parameters such as stride length, time, velocity, and cadence. For each participant and each stepping pattern, the knee force and moment curves for the five trials were normalized to body weight and 100% of the cycle, and then they were averaged to give a single representative trial for each condition. Specific curve locations where forces and moments were maximal, as well as the angular range of motion, were selected for analysis and were compared between stepping patterns separately for ascent and descent, using one-way analysis of variance. Ascent and descent conditions were compared with independent t-tests.

RESULTS

Time–distance parameters. Because the length of the stair run was fixed, the step length for the traditional SOS pattern (two stairs) was longer than that of either SBS pattern. In addition, because the time to complete a step was not different between conditions, the walking velocity for the SOS conditions was faster than for the SBS condition (Table 1).

Stair ascent. For stair ascent, there were differences in the sagittal-plane knee angle, net anteroposterior (AP) force, and net flexion moment across conditions (Fig. 3). For the knee flexion angle, both the peak and ROM were different across all three stepping conditions (Table 1). Visual examination suggested that the SOS condition was more similar to the SBSL condition than to the SBST condition. Similar statistical differences and visual similarities were seen in the AP knee force results. The AP force peak at 50% of the gait cycle was different across conditions, but, again, visual examination showed that the SOS and SBSL conditions were more similar to each other than to the SBST condition.

The flexion moment curves were analyzed using the distinctive peak at the beginning of the stance phase. Here, the results show that the SOS (0.96 N·m·kg⁻¹) and SBSL (0.97 N·m·kg⁻¹) conditions were similar, whereas the SBST (0.14 N·m·kg⁻¹) peak was smaller. Unlike angles, forces, and moments in the sagittal plane, there were no differences in the frontal-plane angles, forces, or moments across conditions (Fig. 4).

During stair ascent, the majority of the muscle power absorbed and generated at the knee joint occurs in the sagittal plane (Table 1 and Figs. 3 and 4), and a large generation peak occurred during the swing phase for both SOS and SBSL (Figs. 3 and 4); however, the magnitudes of these peaks were not significantly different (P > 0.05). This peak is absent for SBS trail leg and exhibits no apparent
power generation or absorption phase throughout stance, indicating that there is a “working” and “supporting” limb during the SBS gait pattern and that these roles do not change, unlike in the case of the SOS pattern, where both limbs perform the same functions at different times.

Stair descent. As was the case with the stair ascent results, the sagittal-plane knee angles, net AP forces, and net flexion moments were different across conditions, whereas the adduction moment did not differ across the stepping conditions (Table 1 and Figs. 3 and 4). Knee angles during stair descent were analyzed using the maximal flexion angle and the total ROM. The three gait patterns were different from each other on both of these measures. The results revealed that the SOS and SBST were larger than the SBSL for both peak and total ROM angles, and, visually, the curve profiles of the SOS and SBST conditions were more similar to each other than to the curve profile of SBSL condition (Fig. 3).

Knee AP force had two peaks. The first peak was larger in the SOS (2.78 N·kg⁻¹) condition than in the two SBS (SBSL, 2.04 N·kg⁻¹; SBST, 1.96 N·kg⁻¹) conditions. For the second peak, the SOS (4.92 N·kg⁻¹) and SBST (4.68 N·kg⁻¹) values were not different, whereas the SBSL (1.57 N·kg⁻¹) peak was smaller than the other two. During the second half of the stance phase, the SOS and SBST curve profiles were more similar to each other than to the SBSL curve profile.

For the knee flexion moment, there were also two main peaks. The first peak was larger in the SOS (0.50 N·m·kg⁻¹) condition than in the two SBS (SBSL, 0.18 N·m·kg⁻¹; SBST, 0.32 N·m·kg⁻¹).

### TABLE 1. Peak joint flexion angles, forces, moments, stepping velocity, and stride length for both step-over-step (SOS) and step-by-step (SBS) ascent and descent stepping patterns.

<table>
<thead>
<tr>
<th></th>
<th>Stride Length (m)</th>
<th>Velocity (m·s⁻¹)</th>
<th>Power (W)</th>
<th>Flexion Angle Peaks (°)</th>
<th>Anteroposterior Force (N·kg⁻¹)</th>
<th>Flexion Moment (N·m·kg⁻¹)</th>
<th>Ab/Adduction Moment (N·m·kg⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>Peak 1</td>
<td>Peak 2</td>
<td>Peak 1</td>
<td>Peak 2</td>
<td>Peak 1</td>
<td>Peak 2</td>
<td>Peak 1</td>
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<td>Ascent</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>SOS</td>
<td>0.62 (0.03)</td>
<td>0.46 (0.06)</td>
<td>91.6 (51.7)</td>
<td>3.95 (0.59)</td>
<td>2.02 (0.59)</td>
<td>0.96 (0.13)</td>
<td>0.25 (0.19)</td>
</tr>
<tr>
<td>SBSL</td>
<td>0.29 (0.01)</td>
<td>0.22 (0.03)</td>
<td>101.5 (26.0)</td>
<td>3.92 (0.55)</td>
<td>1.49 (0.37)</td>
<td>0.97 (0.20)</td>
<td>0.29 (0.14)</td>
</tr>
<tr>
<td>SBST</td>
<td>0.30 (0.01)</td>
<td>0.21 (0.03)</td>
<td>57.3 (6.6)</td>
<td>1.85 (0.51)</td>
<td>1.86 (0.58)</td>
<td>0.14 (0.13)</td>
<td>0.30 (0.11)</td>
</tr>
<tr>
<td>Descent</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SOS</td>
<td>0.61 (0.02)</td>
<td>0.49 (0.07)</td>
<td>177.0 (40.8)</td>
<td>2.78 (0.63)</td>
<td>4.92 (0.79)</td>
<td>0.50 (0.17)</td>
<td>1.50 (0.24)</td>
</tr>
<tr>
<td>SBSL</td>
<td>0.29 (0.01)</td>
<td>0.23 (0.03)</td>
<td>16.6 (17.6)</td>
<td>2.04 (0.53)</td>
<td>1.57 (0.40)</td>
<td>0.27 (0.23)</td>
<td>0.18 (0.17)</td>
</tr>
<tr>
<td>SBST</td>
<td>0.29 (0.01)</td>
<td>0.24 (0.04)</td>
<td>149.9 (28.9)</td>
<td>1.96 (0.37)</td>
<td>4.68 (0.81)</td>
<td>0.34 (0.17)</td>
<td>1.11 (0.23)</td>
</tr>
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All numbers are presented as means (SD). Values with similar superscripts are not significantly different at P < 0.05 according to Duncan’s post hoc test.

SBST, 1.11 N·m·kg⁻¹) conditions. For the second peak, the SOS (1.05 N·m·kg⁻¹) and SBST (1.11 N·m·kg⁻¹) were not different, whereas the SBSL (0.18 N·m·kg⁻¹) peak was smaller. Again, the SOS and SBST condition curve profiles were more similar to each other than to the SBSL curve profile.

As in the case of the stair ascent, during stair descent the majority of power absorbed and generated at the knee joint occurs in the sagittal plane. During descent, a large absorption peak occurs in late stance for both SOS and SBST (Table 1 and Figs. 3 and 4). However, the lead leg of SBS exhibits no absorption or generation peak throughout the entire stance phase. Additionally, the absorption peak for SOS is significantly greater than SBST (P < 0.05). Again, similar to stair ascent, the working and supporting limbs during the SBS gait pattern have similar roles, in contrast to the SOS pattern, where both limbs perform the same functions at different times.

Unlike the SOS pattern, during the SBS pattern each leg (lead or trail) performs a different function. During SBS ascent, the trail leg provides support, indicated by the lack of sagittal-plane power generation, whereas during stance the lead leg raises the body up to the next step. These functions are the same as those performed during SOS ambulation, with the difference being that in the SBS ambulation the legs do not change roles; the trail leg remains the trail leg, and the lead leg remains the lead leg. This happens in SBS descent as well. In SBS descent, the lead leg provides support and the trail leg is responsible for controlling the lowering of the body. The lead leg during ascent and the trail leg during descent were the working limbs in that they experienced high AP forces, powers, and flexion moments, similar in magnitudes to those measured in the SOS ascent and descent patterns. Conversely, the support limbs were the trail leg during ascent and the lead leg during descent, because the AP forces, powers, and moments were lower than either the working limbs in the SBS pattern or the SOS pattern. The SBS working limbs during both ascent and descent were similar to the SOS profiles (Fig. 3).

**DISCUSSION**

Simply on the basis of the range of motion that you travel, you would expect that the traditional SOS stair ambulation pattern would be very different from the compensatory SBS pattern. Indeed, the step length is longer for the SOS pattern and results in an increased stride velocity. The resultant stride length and stride velocity during ascent and descent were comparable with values reported by Nadeau et al. (16).

During the SOS pattern, each limb performs the same function at different times. As with previous investigations (14,19), initiation of the SOS stance-phase ascent in our study produced large sagittal-plane power-generation peaks, suggesting that the knee of the lead leg is responsible for pulling the body up from the lower step. Once the trail leg clears the stair, it takes over as the lead leg and continues
through to the next step. During the SOS ascent gait cycle, there are no other power-generation phases at the knee, so the movement of the contralateral limb to the subsequent step is the responsibility of the ankle and the contralateral hip flexors (14,19). During SOS descent, the knee’s sagittal-plane power profiles suggest that the lowering of the body is controlled by the trail leg while the lead leg reaches for the lower step. Once on the lower step, the lead leg becomes the trail leg, and the next cycle begins. Clearly, this is not the case with the SBS pattern.

SOS ascent peak flexion moments were similar to those reported in other investigations (4,12), and the SBS working limb had similar values to SOS during both ascent and descent. Supporting limb flexion moments were lower by comparison with the working limb. The reduced flexion moments seen in the SBS support limb could have clinical implications, because individuals with chronic knee pain typically demonstrate reduced peak flexion moments during stair ambulation (10,20,17).

It is likely that patients with knee osteoarthritis and patellofemoral pain adapt their gait to minimize knee flexion moments to reduce joint reaction forces at the knee joint (10,20), and results from this study suggest that knee pain may be reduced during stair ascent by using the more painful leg as the support or trail leg. Furthermore, the literature has shown that effective stair climbing requires approximately 1.0 N·m·kg⁻¹ of extensor muscle moment (16), whereas in this study, SBS peak flexion moment of the support limb was less than 0.3 N·m·kg⁻¹, a much greater reduction. Thus, one potential reason for using the SBS pattern is the increased difficulty in stair ambulation associated with decrements in motor function (i.e., muscular strength, proprioception). The SBS pattern allows for a shorter and slower stride, which may increase stability and compensate for lower-limb weaknesses. However, this must be taken with the realization that individuals using this gait pattern will have to take twice as many strides to cover the same distance.

The most interesting feature seen by examining the joint angle, force, and moment curve profiles in this study is that the profiles for the working legs are very similar whether you consider ascent or descent. Although there are some statistical differences, the curves are surprisingly similar at the time of maximum load. In hindsight, this might seem obvious, because it does not matter whether you use the traditional stepping pattern or a modified stepping pattern: you must still move your body to the next step, which, regardless of the stepping pattern, requires the same amount of work.

The current study used young, healthy volunteers to determine the effect of an SBS stair ambulation pattern on the biomechanics of the knee. Thus, an important caveat is that the results reflect changes in the stepping pattern, and not additional compensations attributable to aging or disease. When alternate stepping patterns are performed by healthy participants, any differences in the mechanics between the two stepping patterns can be attributed to the patterns, rather than to the individual’s ability to perform the pattern. However, this may be quite different when comparing the SOS pattern of one group against the SBS pattern of another group that is not capable of performing the SOS pattern. The data presented here can be used to highlight compensations that occur in addition to a change in the stepping pattern. We now know that the compensatory SBS ambulation pattern should resemble the traditional SOS ambulation pattern, if we consider the support and working legs. Significant deviations from the typical pattern would suggest additional compensations (i.e., muscle weakness, balance, etc.) that must be considered over and above the altered stepping pattern. The moments and forces are similar between the SBS and SOS patterns, and it is likely that the increased physical demands placed on the knee joint, coupled with the reduced physical capacity of select populations, are responsible for these alterations. Future studies are needed to determine the reasons, both actual and perceived, why an alternate stepping pattern is chosen.

The angle, force, power, and moment patterns at the knee joint of normal reciprocal SOS stepping pattern and alternate SBS stepping pattern have been presented for a group of young, healthy adults. The resulting curve profiles establish normative profiles for stair ambulation patterns that can be used to evaluate whether changes in knee joint mechanics are attributable solely to ambulation patterns, or whether additional compensations are present. Moreover, the results have clinical implications for the reduction of knee pain in populations with chronic knee pain. This will be important when evaluating stair ambulation performance in patients, older adults, and disabled populations.

REFERENCES


