Pelvifemoral Kinematics While Ascending Single Steps of Different Heights

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Motion of the femur and pelvis during hip flexion has been examined previously, but principally in the sagittal plane and during nonfunctional activities. In this study we examined femoral elevation in the sagittal plane and pelvic rotation in the sagittal and frontal planes while subjects flexed their hips to ascend single steps. Fourteen subjects ascended single steps of 4 different heights leading with each lower limb. Motion of the lead femur and pelvis during the flexion phase of step ascent was tracked using an infrared motion capture system. Depending on step height and lead limb, step ascent involved elevation of the femur (mean 47.2° to 89.6°) and rotation of the pelvis in both the sagittal plane (tilting: mean 2.6° to 9.7°) and frontal plane (listing: mean 4.2° to 11.9°). Along with maximum femoral elevation, maximum pelvic rotation increased significantly \( p < .001 \) with step height. Femoral elevation and pelvic rotation during the flexion phase of step ascent were synergistic \( (r = .852–.999) \). Practitioners should consider pelvic rotation in addition to femoral motion when observing individuals’ ascent of steps.

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Numerous studies have established that shoulder abduction and flexion are accomplished by a combination of elevation of the humerus and upward rotation of the scapula (Crosbie et al., 2008; Price et al., 2000). Research over the past 25 years has demonstrated that hip flexion (angular approximation of the thigh and anterior trunk) is likewise dependent on a combined elevation of the femur and rotation (posterior tilting) of the pelvis. The research shows that 13.1–37.1% of the hip flexion of individuals who are supine, standing, or suspended from a bar can be attributed to sagittal plane tilting of the pelvis (Bohannon 1982; Bohannon et al., 1985a, 1985b; Congdon et al., 2005; Dewberry et al., 2003; Murray et al., 2002). The aforementioned research, though diverse, does not address pelvifemoral rhythm during a common functional activity. Other research has described the kinematics of the femur and pelvis during level-ground gait (Bejek et al., 2006; Crosbie & Vachalathiti, 1997; Taylor et al., 1999), a functional activity requiring only minimal hip flexion. That research demonstrates that the pelvis rotates in both the sagittal plane (tilts) and frontal plane (lists) during the walking cycle and that the list in the frontal plane is phase-locked with hip flexion (Crosbie & Vachalathiti, 1997).

If hip flexion is accompanied by sagittal and frontal plane tilting of the pelvis, then both may be relevant to the manner in which individuals perform functional activities such as ascent of a step which require such flexion. This possibility led to the present investigation, the purpose of which was to describe pelvifemoral kinematics while the hip was flexed to ascend single steps of different heights. We hypothesized that hip flexion would involve femoral elevation and pelvic rotation (both sagittal and frontal) and that the femoral and pelvic motions would be related to one another over the course of hip flexion. We also hypothesized that ascent of progressively higher steps would be associated with increases in maximum femoral elevation and pelvic rotation.

Methods

Subjects

A convenience sample of 8 men and 6 women (26.2 ± 9.2 years old) participated. None reported current orthopedic or neurologic problems affecting function. To allow for accurate and unobscured placement of markers, no subjects were obese (body mass index = 23.5 ± 2.2 kg/m²). Before participation, all signed a consent form approved by the Institutional Review Board of the University of Connecticut.

Instrumentation and Procedures

Three-dimensional movement kinematics were captured at 240 Hz using a seven-camera infrared Qualisys Motion Capture System. Before initiating motion capture, the system was calibrated to establish the location of the
cameras and orient them to the laboratory coordinate system. Thereafter, subjects were fitted with 27 reflective markers for the static calibration trial (Figure 1 [left]). The static calibration trial captured in the standing anatomical position was performed to create the coordinate system for each bone segment. After this trial, the 10 markers used to establish the proximal and distal ends of the lower limb segments (i.e., hip, knee, ankle) were removed. This left 17 reflective markers used in subsequent analysis: clusters of 3 on each shank, on each thigh, and over the sacrum, as well as 1 just lateral to each anterior superior iliac spine (Figure 1 [right]). Subjects then performed 24 stepping trials onto a single aerobic step (10.1 cm, 20.3 cm, 30.5 cm, 40.6 cm) placed 25 cm in front of their toes. Three stepping trials were performed at each height leading with each lower limb in a random, blocked order. That is, there was a randomization of the order in which subjects stepped up with their left or right limb and of the order in which step heights were negotiated. Before stepping, subjects were given instructions. Specifically, they were told to: (1) stand with weight evenly distributed, (2) step up at a comfortable speed, (3) feel free to look at the step but not bend forward at the waist if doing so, (4) not use their hands to push on their thighs, and (5) return to symmetrical weight-bearing once standing on the step. Each step up commenced after the command “ready, step right” or “ready, step left.”

To ensure the recording of static standing before and after stepping, each step trial involved 4 s of motion capture. Data processing required that each marker be identified and tracked. If any marker was obscured during the movement, a spline-fitting program filled the marker gaps (Qualisys Tracking software). The tracked data were then transferred to Visual 3 D software. There the data were smoothed (low-pass filtered at 6 Hz) and the positions of the bones (femurs and pelvis) in space and relative angles were calculated. A model was used that allowed the tracking of femoral motion in the sagittal plane (around the x axis) and pelvic rotation in the sagittal plane (around the y-axis: tilting) and frontal plane (around the y-axis: listing).

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**Figure 1** — Anterior-posterior view of the reflective marker configuration used. The full array of markers used for calibration is shown on the left. The dark markers, which represent joints, were removed before step trials. The markers retained for tracking are shown on the right during an actual stepping trial. Note how the right hip is flexed and the right pelvis is tilted upward during step ascent.
Data Analysis

Data of interest were elevation of the lead femur and rotation of the pelvis in the sagittal and frontal planes as subjects ascended steps leading with each lower limb. Observation of the skeletal model and visual inspection of digital coordinates provided for the determination of the initiation and point of maximum hip flexion while subjects ascended single steps with each lower limb. The positions (angular excursion) of the femur in the sagittal plane and of the pelvis in the sagittal and frontal planes were determined relative to static standing before the initiation of flexion of the lead lower limb. To allow for the comparison and consolidation of data across trials, motion of the femur and pelvis over the course of hip flexion was characterized by breaking each trial (initiation of flexion to maximum flexion) into 10 equal time segments (11 points). Maximum femoral elevation and pelvic rotation (sagittal and frontal) were also identified. These data were entered into an Excel file and imported into the Statistical Package for Social Sciences (SPSS, version 14.0). Descriptive statistics were calculated for both segmental and maximum femoral and pelvic motions. As data from repeated trials were acceptably reliable (mean intraclass correlation coefficient ≥ .800), the average of the 3 trials was used in all subsequent analysis. Line graphs were plotted using segmental points and the relationship of femoral elevation and pelvic rotation over the course of hip flexion was determined using Pearson product–moment correlations. General linear model (GLM) procedures for repeated measures were used to compare maximum femoral elevation and pelvic rotations of each side across the 4 step heights. To further delineate the effect of step height on femoral elevation and pelvic rotation, planned contrasts (difference and polynomial [trend analysis]) were conducted.

Results

This study demonstrated that the hip flexion associated with ascending steps involved both elevation of the femur and rotation of the pelvis in the sagittal and frontal planes. Specifically, as the hip flexed the pelvis tilted posteriorly and listed upward on the side of the elevated femur. Figure 2 illustrates this concurrent motion for each step height. Both sagittal and frontal motion of the pelvis can be seen to accompany sagittal elevation of the femur from early in the hip flexion motion. Depending on step height and side, the Pearson correlations ranged from .977 to .999 between femoral elevation and pelvic tilt, from .917 to .983 between femoral elevation and pelvic list, and from .852 to .998 between pelvic tilt and list. Table 1 summarizes the maximum elevation of the femur and rotation of the pelvis during ascent of steps of different heights. The GLM analysis showed step height to have a significant effect (p < .001) on femoral elevation whether stepping up with the right or left lower limb. The GLM analysis also demonstrated that step height had a significant effect on rotation of the pelvis in the sagittal and frontal planes (p < .001), regardless of the lead lower limb. Planned contrasts also showed that both the hip and pelvic motion differed between all steps heights (p < .001) and that the effects of step height on femoral and pelvic motion were linear (p < .001).

Discussion

Like previous research focused on hip flexion in isolation or addressing hip flexion during gait (Bejek et al., 2006; Bohannon, 1982; Bohannon et al., 1985a, 1985b; Congdon et al., 2005; Crosbie & Vachalathiti, 1997; Dewberry et al., 2003; Murray et al., 2002; Taylor et al., 1999) our study shows that elevation of the femur is accompanied by pelvic rotation. Pelvic rotation, which began soon after femoral elevation commenced, was correlated highly with femoral elevation. Thus, the pelvifemoral synergism that Crosbie and Vachalathiti (1997) described as existing during the walking cycle, is also present during the flexion phase of step ascent.

Ours may be the first research to describe the magnitude of both femoral elevation and pelvic rotation while ascending a step of different heights. The mean maximum femoral elevation demonstrated in our study (47.2° to 89.6°, depending on step height) encompasses the mean maximum hip flexion angles (66.1° to 76.9°) reported by Rainer et al. (2002) for steps of 13.8 cm to 22.5 cm. Compared with the mean pelvic rotation values that Crosbie and Vachalathiti (1997) reported for subjects walking at preferred (sagittal = 4.6°, frontal = 6.9°) or fast (sagittal = 6.2°, frontal = 9.9°) speeds, the pelvic rotation of our subjects was less during ascent of the 2 lower height steps and greater during ascent of the highest step.

As would be expected on the basis of logic and previous research (Riener et al., 2002), femoral elevation was found to increase in concert with the step height. That maximum pelvic rotation increased as well, is a new finding. It would appear that just as the femur is elevated to enable ascent, the pelvis rotates. Specifically the pelvis tilts posteriorly and lists (elevates) laterally on the side of the advancing limb. Thus, maneuvers that are classified as gait deviations when extreme (e.g., hip-hiking) may merely be natural accommodations to functional challenges.

Our results should be interpreted in light of several limitations. First, our subjects climbed a single step. The kinematics may therefore be different than when climbing consecutive steps. Second, the subjects started ascent from a standing start in which their toes were 25 cm from the step. This probably affected the way they advance their lead limb, particularly when attempting to ascend the higher steps. Qualitatively it appeared that some subjects actually rotated their pelvis slightly away from the step in the horizontal plane (around the z-axis) to make room for their advancing limb. In future research, we intend to allow a step before ascent so that kinematic analysis will begin during a condition of unilateral stance. Third,
Figure 2 — Line graphs illustrating movement of femur and pelvis during ascent of steps of 4 heights leading with the left limb (left column) or right limb (right column).
our subjects were healthy. While we chose such subjects intentionally, their kinematics may differ from those of subjects with impairments in balance, strength, or range of motion. The consequences of such impairments warrant further investigation. Finally, our sample size was small. Although the number of subjects did not preclude the realization of highly significant results, it was too small to justify analysis of variables such as stature and gender that might modulate pelvifemoral kinematics.

In conclusion, hip flexion to ascend a step of different heights involves both femoral elevation and rotation of the pelvis in the sagittal and frontal planes. Such rotation appears to be normal rather than deviant or compensatory.

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References


