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Hip and knee flexion of lead and trail limbs during ascent of a step of different heights by normal adults

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Abstract

Objective To describe and compare hip and knee flexion of the lead and trail limbs during step ascent.
Design Descriptive observational study.
Setting University research laboratory.
Participants Fourteen healthy subjects.
Main outcome measures A seven-camera tracking system captured the kinematics of the lead and trail limbs as subjects ascended 20.3-cm and 40.6-cm steps, leading with each lower limb. Maximum hip and knee flexion were recorded bilaterally.
Results During ascent of the 20.3-cm step, mean flexion was 66.3° for the lead hips and 20.6° for the trail hips [mean difference 45.7°, 95% confidence interval (CI) 43.5° to 48.0°]. During ascent of the 40.6-cm step, mean flexion was 92.5° for the lead hips and 26.8° for the trail hips (mean difference 65.6°, 95% CI 62.1° to 69.1°). During ascent of the 20.3-cm step, mean flexion was 90.5° for the lead knees and 57.6° for the trail knees (mean difference 32.9°, 95% CI 29.3° to 36.5°). During ascent of the 40.6-cm step, mean flexion was 119.9° for the lead knees and 73.2° for the trail knees (mean difference 46.7°, 95% CI 41.9° to 51.5°). A general linear model revealed that for both the hip and the knee, flexion was significantly greater in the lead limb than in the trail limb, and during ascent of the 40.6-cm step compared with the 20.3-cm step.
Conclusions The hip and knee flexion used to ascend a step depends on whether a limb is leading or trailing, and on step height. For individuals with limited flexion in a limb, range demands will be reduced if the restricted limb trails during a step-to-step pattern.

Keywords: Kinematics; Knee; Hip; Gait; Steps

Introduction

In residence and out in the community, individuals frequently have the need to step up on to a higher surface. Whether the step involves a kerb, stool, stair or ladder, ascent is normally accomplished through flexion of the hip and knee. The magnitude of flexion at these joints during stair negotiation has been studied extensively. On steps with a height between 13.8 cm and 22.5 cm, research has shown maximum hip flexion to range from a mean of 40.8° to 76.9°, and maximum knee flexion to range from a mean of 73.4° to 105.3° (Table 1) [1–7]. These findings were determined using a step-over-step pattern of ascent. Such a pattern is not always possible or advisable for patients with musculoskeletal impairments in strength or range of motion, or who have pain or weight-bearing restrictions. Such patients may have to ascend each step leading with the same limb (using a step-to-step pattern). Maximum hip and knee flexion has not been described for the lead and trail limbs when using a step-to-step pattern to ascend a step. Knowledge of the flexion required of both limbs during such a pattern of ascent is important if appropriate expectations and therapy goals are to be established.

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Table 1
Maximum hip and knee flexion range-of-motion during stair ascent of healthy subjects in seven studies.

Study	Subjects	Steps	Mean hip flexion (°)	Mean knee flexion (°)
Laubenthal *et al.* [3]	30 men Mean age: 25 years Mean height: 1.78 m	$n=2$ Height: not reported	Not reported	83.0 (floor to step 2)
Andriacchi *et al.* [1]	10 men Age: 20 to 34 years Mean height: 1.79 m	$n=3$ Height: 21.0 cm	40.8 (step 1 to step 3) 41.9 (floor to step 2)	73.4 (step 1 to step 3) 83.3 (floor to step 2)
Jevsevar *et al.* [2]	11 subjects Mean age: 52.5 years Mean height: 1.60 m	$n=4$ Height: 18.0 cm	Not reported	92.9 (right) 90.8 (left)
Salsich *et al.* [7]	Five men and five women Mean age: 31.9 years Mean height: 1.71 m	$n=3$ Height: 20.5 cm	68.4	73.8
Riener *et al.* [6]	10 men Mean age: 28.8 years Mean height: 1.79 m	$n=5$ Height: 13.8, 17.0 and 22.5 cm	66.1 (13.8 cm) 69.1 (17.0 cm) 76.9 (22.5 cm)	91.2 (13.8 cm) 94.6 (17.0 cm) 105.3 (22.5 cm)
Livingston *et al.* [4]	Six subjects Age: 19 to 26 years Mean height: 1.64 m	$n=6$ Height: 12.7 and 20.3 cm	52.3 (12.7 cm) 52.0 and 61.0 (20.3 cm)	87.3 (12.7 cm) 99.7 and 100.7 (20.3 cm)
Protopapadaki *et al.* [5]	16 men and 17 women Age: 18 to 39 years Mean height: 1.69 m	$n=4$ Height: 18 cm	65.1	93.9

Objectives

The aim of this study was to describe the ranges of hip and knee flexion demonstrated in the lead and trail limbs while subjects stepped on to a single step (height 20.3 cm or 40.6 cm) using a step-to-step pattern. It was hypothesised that hip and knee flexion would be: (1) significantly greater for the lead limb compared with the trail limb; (2) significantly greater for the 40.6-cm step compared with the 20.3-cm step; and (3) not significantly different when leading with the right limb compared with the left limb.

Methods

Design

This study had a cross-sectional, observational design. It was approved by the Institutional Review Board of the University of Connecticut, USA.

Participants

All 14 subjects (eight males, six females), who were apparently healthy volunteers from the university community, participated with written informed consent. Mean age was 26.9 ± 9.2 years and mean height was 172.6 ± 9.9 cm. None of the subjects were obese (mean body mass index 23.5 ± 2.2 kg/m^2), and none of them reported any current orthopaedic or neurological conditions that would affect step ascent.

Instrumentation and procedure

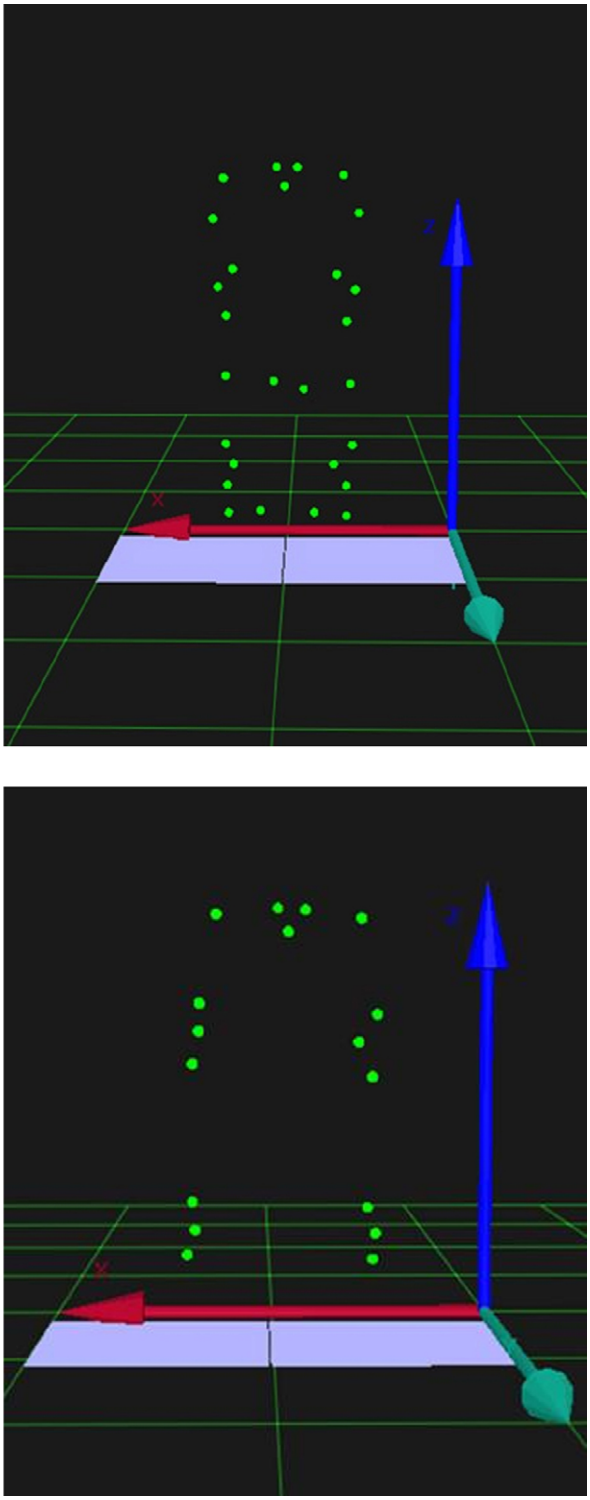
Three-dimensional movement kinematics were captured using a seven-camera Qualisys Motion Capture System (Qualisys AB, Gothenburg, Sweden). The cameras emit infrared light that reflects off passive markers placed on specific anatomical landmarks on the subjects. The signal received from the cameras is then sent to the computer where Visual3D software (Qualisys AB, Gothenburg, Sweden) is used to create a model from which kinematics are determined.

Prior to trials, the system was calibrated to orient the cameras with the laboratory coordinate system. Subjects were then fitted with 27 markers for a static calibration trial that was used to create a representation of bone segments relevant to the study (Fig. 1a). The anatomical locations of these markers were:

- one just lateral to each anterior superior iliac spine;
- one over each trochanter;
- three on a rigid plate over the sacrum (two in line with the posterior superior iliac spines);
- three on a rigid plate over the anterolateral portion of each thigh;
- three on a rigid plate over each shank;
- one on each medial and lateral knee joint line; and
- one on each malleoli [8].

After the static calibration, 10 markers were removed (two trochanter, four knee joint line, four malleoli) leaving 17 markers (Fig. 1b).

Subjects performed 12 stepping trials on to a single aerobic step of two heights. The heights were those approximating a standard step (20.3 cm) or two standard steps (40.6 cm). Each trial began with the subject's toes 10 cm from the step. Three stepping trials were performed at each height with each lower limb leading. The order of lead side (right or left) and step height (20.3 cm or 40.6 cm) was assigned at random before the trials began. Prior to stepping, the subjects were given the following specific instructions:



(a) (b)

Fig. 1. Marker set-up used to track lower limbs during step ascent. Marker positions on lower limbs and pelvis during (a) static calibration and (b) step ascent trials.

- stand with weight evenly distributed;
- step up at a comfortable speed;
- look at the step if necessary but do not bend at the waist to do so;
- do not push on your thighs for leverage; and
- return to evenly distributed weight bearing once on the step.

The step command prior to each trial was 'ready, step right' or 'ready, step left'. Upon completion of each trial, the subjects were given a 'step down' command and instructed to return to the starting position 10 cm from the step.

Step trials were captured at 240 Hz. Despite the use of a multi-camera system, the representation of markers was occasionally lost. In such cases, the computer system utilises a spline-fitting program to gap-fill missing data according to a best fit along the slope of the data. Once all gaps were filled (none greater than 0.1 second or 3% of capture) and markers were labelled, the saved file was transferred to a Visual3D software system.

The Visual3D smoothed the data at 6 Hz and created a visual representation of the bone segments in space that enabled the relative joint angles to be calculated. The visual representations of the sagittal excursion of both the hip and knee in space for both lead and trail lower limbs were displayed on graphs. These graphs were used to identify maximum hip and knee flexion angles for each trial, which were recorded in an Excel file.

Data analysis

Statistical Package for the Social Sciences, Version 14.0 (SPSS Inc., Chicago, IL, USA) was used for data transformation and analysis. Based on the reliability of the data (coefficient of individual subject variation: 2 to 12% for hip flexion and 1 to 6% for knee flexion), the average of the three trials for both hip and knee, and lead and trail lower limb were determined and used in the subsequent analysis. Thereafter, descriptive statistics were calculated and a general linear model was used to determine the effect of limb (lead vs. trail), step height (20.3 cm vs. 40.6 cm) and side (right vs. left) on maximum hip and knee flexion.

Results

This study demonstrated that step ascent by normal subjects employing a step-to-step gait pattern requires flexion of the hips and the knees of both the lead and trail lower limbs. Table 2 summarises the maximum flexion for the hip and knee according to step height, side and limb. It is clear that flexion of both the hip and knee is greater for the lead lower limb compared with the trail lower limb. Flexion was also greater for the 40.6-cm step compared with the 20.3-cm step for both the lead and trail limbs.

The general linear model analysis demonstrated that limb (lead vs. trail) had a significant effect on maximum flexion of both the hip ($F = 2038.16$, $P < 0.001$) and the knee ($F = 492.02$, $P < 0.001$). The analysis also demonstrated that step height (20.3 cm vs. 40.6 cm) had a significant effect on the maximum flexion of both the hip ($F = 703.77$, $P < 0.001$)

Table 2
Descriptive statistics summarising maximum hip and knee flexion (°) during step ascent.

Step height (cm)	Lead side	Lead hip range mean (S.D.)	Trail hip range mean (S.D.)	Hip mean difference (95% CI)	Lead knee range mean (S.D.)	Trail knee range mean (S.D.)	Knee mean difference (95% CI)
20.3	Right	66.2 (5.5)	20.6 (4.7)	45.6 (43.2 to 48.1)	90.8 (7.8)	57.0 (8.8)	33.8 (29.9 to 37.7)
	Left	66.4 (4.6)	20.6 (4.8)	45.8 (42.2 to 49.4)	90.2 (6.9)	58.2 (6.6)	32.0 (26.2 to 37.7)
40.6	Right	92.0 (5.9)	26.8 (4.0)	65.3 (62.9 to 68.3)	119.7 (5.2)	73.2 (7.3)	46.5 (43.1 to 49.8)
	Left	92.9 (5.00	26.9 (6.1)	66.0 (61.2 to 70.7)	120.2 (7.9)	73.2 (8.9)	47.0 (39.2 to 54.8)

S.D., standard deviation; CI, confidence interval.

and the knee ($F = 573.26$, $P < 0.001$). Side (leading with the right or left) had no significant effect on maximum flexion of the hip or the knee. There was a significant interaction between limb (lead vs. trail) and step height for both the hip ($F = 288.12$, $P < 0.001$) and the knee ($F = 72.22$, $P < 0.001$). This interaction indicates that the difference in flexion between the lead and trail lower limbs was accentuated during ascent of the higher step.

Discussion

Previous research has extensively examined the hip and knee kinematics of the lead lower limb during step-over-step stair ascent [1–7]. This study is different in that it examined both the lead lower limb and the trail lower limb during step-to-step ascent.

In keeping with previous research on the ascent of multiple steps, this study showed that ascent of a single step involved flexion of both the hip and the knee. When comparing step heights of 17.0 to 22.5 cm in previous studies [1–7] with the 20.3-cm step used in this study, the magnitudes of hip and knee flexion were quite similar. This validates the results obtained for the lead lower limb in this study, and suggests that the results determined for the trail lower limb may also be accurate.

This study determined that maximum hip and knee flexion of both the lead and trail lower limbs were greater when stepping on to a 40.6-cm step compared with a 20.3-cm step. The study also showed that maximum flexion of the trail lower limb was significantly less than that of the lead lower limb, regardless of step height. These results have some practical application for treatment of patients with impairments and activity limitations. Therapists commonly instruct patients with limited range of motion, strength or pain to ascend steps in a step-to-step pattern leading with their ‘good limb’. This research provides an indication for the functional range required for utilising this pattern. This may offer therapists an objective way of assessing whether or not a patient is ready to ascend stairs in a normal fashion. It may also provide the therapist with an opportunity to create an objective range-of-motion goal for a patient who is having difficulty ascending stairs.

This study had several limitations. The first limitation was the loss of markers during Qualisys motion capturing. This was a problem in spite of the use of a seven-camera system. It was aggravated by the fact that the higher step blocked the line of view of several cameras at the initiation of stepping. Although the system does fill the gaps, the corrected slopes are still based on statistical imputations and not the actual recorded movements. A second limitation is that the subjects were required to start 10 cm from the step. This may have forced the subjects to use a different pattern of movement than if they were allowed a step before ascent, thus altering their preferred stepping kinematics. Perhaps future studies should allow subjects to begin each trial dynamically; that is, by taking a single step on level ground prior to stepping on to the step. Finally, this study was performed using healthy subjects, and the results may differ for patients with impairments in strength, range of motion, balance or sensation. Future studies should look at patients with such impairments. This would provide information on whether the stepping patterns of these patients are similar to those of the healthy subjects described in this study and other published literature.

Conclusions

When climbing a single step, hip and knee flexion are significantly greater in the lead limb compared with the trail limb. Hip and knee flexion are significantly greater during ascent of a 40.6-cm step compared with ascent of a 20.3-cm step. Thus, individuals with limited hip and knee flexion may be able to ascend a step with a normal pattern provided that the limitations are in the trail limb.

Ethical approval: Institutional Review Board of the University of Connecticut (Ref. No. H06-303).

Conflict of interest: None declared.

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