# Does the choice of stair gait cycle affect resulting knee joint kinematics and moments?

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# Does the choice of stair gait cycle affect resulting knee joint kinematics and moments?

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**Abstract:** Stair gait is a useful activity for the assessment of knee function. The aim of this study was to determine whether knee joint kinematics and moments are affected by the choice of stair gait cycle (SGC) and the step used to measure ground reaction forces (GRFs). This was investigated through motion analysis of ten non-pathological subjects as they ascended and descended a four-step staircase. The SGCs compared for ascent were, first, step 1 (measuring GRFs) to step 3 and, second, step 2 (measuring GRFs) to step 4, and vice versa for stair descent. Knee joint kinematics were not significantly influenced by the choice of SGC. For ascent, significantly larger peak adduction moments were measured for SGCs beginning on step 1 ($0.30 \pm 0.08$ N m/kg) than for SGCs beginning on step 2 ($0.23 \pm 0.09$ N m/kg). For descent, the second flexion moment peak was found to be significantly larger for SGCs ending on step 2 ($1.17 \pm 0.25$ N m/kg) than for SGCs ending on step 1 ($0.97 \pm 0.19$ N m/kg), and the first adduction moment peak was found to be significantly larger for SGCs ending on step 2 ($0.28 \pm 0.15$ N m/kg) than for SGCs ending on step 1 ($0.21 \pm 0.18$ N m/kg). This study highlights important considerations when planning stair gait measurement protocols and comparing results from studies made by other laboratories.

**Keywords:** stair gait cycle, stair ascent, stair descent, knee joint moments, knee kinematics, motion analysis

## 1 INTRODUCTION

When assessing knee function using motion analysis techniques, valuable biomechanical data can be obtained from a range of daily activities. Stair ascent and descent have been shown to have significantly lower variability than level walking [**1**], owing to the higher level of motor activity required by the muscles. Stair ascent and descent have been used successfully by a number of studies to assess the knee joint during high flexion and under high-loading conditions. Examples include motion analysis of stair gait, first, to quantify non-pathological (NP) knee function [**1–6**], second, to investigate the effect of age [**7–11**], step height [**9**, **12–14**], and body mass [**14**] on knee biomechanics, third, to investigate the function characteristics associated with anterior cruciate ligament (ACL) deficiency [**15**] and reconstruction [**16**], osteoarthritis [**17**], and surgical intervention [**16**, **18**, **19**], and, fourth, to investigate falls [**20**].

The choices of anatomical calibration and computational approaches have been shown to influence resulting knee joint kinematics and moment outputs [**21**]. Additional considerations when designing a methodology for assessing stair gait are the choice of stair gait cycle (SGC) and the step used to measure ground reaction forces (GRFs). These may also affect outputs and prevent a direct comparison between the kinematic and kinetic data obtained in similar studies. The number of steps in a staircase varies in different studies, as highlighted in reference [**9**]. This provides several levels at which to measure the GRF during stair ascent and descent. In addition to this, there are a variety of staircase designs in use [**22**], which will also influence the choice of step used to measure GRFs.

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The first two steps of a staircase provide the transition from level walking to stair ascent and from stair descent to level walking [**9**, **23**]. During these transition stages, the subject is required to adjust their motion continually. It has been found that, as a subject ascends from floor level to step 2 of the staircase, the intra-subject reproducibility of kinematics and moments improves. As a subject descends from step 2 of a staircase, the kinematics and moments become less reproducible when stepping to floor level [**23**]. Thus variability is most affected during the transition stage and decreases in steady state stair gait. The difference between the strategies for the transition and midstair region of stair descent has been reported by Christina and Cavanagh [**7**]. The transition stage is an important consideration in studies assessing stair gait symmetry of the right and left lower limbs and where the SGCs and step measuring GRFs are not consistent for the right leg and left leg under investigation. It has been suggested that, for studies where gait symmetry is important, a minimum of a five-step staircase is necessary to ensure that the left-to-right symmetry of two consecutive steps is not affected by choice of step to record the GRF [**9**]. The current design of the staircase was developed for studies involving subjects with osteoarthritis. As stair ascent and descent are difficult for these subjects, the staircase was designed to be least demanding for them, while having a sufficient number of steps to obtain a gait cycle from both legs for ascent and descent. Since the same SGCs are considered for each leg, rather than using cycles from different stages of a larger staircase, gait symmetry could be examined but is not an important issue for this study. Several studies, which are often limited by height restrictions in the laboratory or by the mobility of the patients under investigation, use a staircase with fewer than five steps and measure GRF from a combination of floor level, step 1, and step 2, as detailed in Table 1 [**2**, **3**, **6–9**, **11**, **14–18**]. These studies highlight the different methodologies currently employed and emphasize that any differences in knee joint biomechanics associated with different SGCs would prevent direct comparison between studies. Any differences would also prevent measurements of the right leg and left leg during ascent of a four-stair staircase from one measurement of ascent and descent [**17**].

Andriacchi *et al.* [**2**] and Kowalk *et al.* [**3**] compared SGCs of a three-step staircase. Andriacchi *et al.* [**2**] identified differences in knee flexion, flexion moment, and adduction moment associated with gait cycles measuring GRFs from floor level and step 1 of a three-step staircase. However, Kowalk *et al.* [**3**] compared maximum knee moments computed from GRFs measured from step 1 and step 2 of a three-step staircase and found no significant differences. When four steps are used, the approach to ascending and descending stairs is expected to change to a more steady state as a full gait cycle of the right leg and left leg is performed. It is important to determine the potential differences in moments and kinematics observed with a four-step staircase, where the GRFs are measured from steps 1 and 2.

A greater understanding of the transition stage of stair gait is important when measuring lower-limb function, and in particular when assessing pathology and recovery where it is common to select a gait cycle where GRFs are measured from step 1 or step 2. In level gait studies, it is routine to select a gait cycle midway through a walking sequence (e.g. after four gait cycles), where sufficient force plate contact has been made. However, for the assessment of stair gait using a four-step staircase, is the choice of gait cycle important? There are several SGCs that can be selected, each subjecting the lower limbs to different inertial effects and biomechanical demands. In studies where, owing to limited resources, the data collection set-up allows forces to be measured from only one step, it is essential to establish whether the step chosen to measure the GRFs is important. In these situations a choice has to be made or

**Table 1** Summary of GRF measurement locations for selected studies of stair climbing

| Number of steps | Study | GRF measurement locations |
|---|---|---|
| 3 | Andriacchi and co-workers [**2**, **16**, **18**] | Floor and step 1 |
| | Kowalk *et al.* [**3**] | Step 1 and step 2 |
| | Thambyah *et al.* [**15**] | Step 2 |
| 4 | Protopapadaki *et al.* [**6**] | Step 2 |
| | Nadeau *et al.* [**8**] | Floor, step 1 and step 2 |
| | Reeves *et al.* [**11**] | Floor and first three steps |
| | Spanjaard *et al.* [**14**] | Floor and first three steps |
| | Kaufman *et al.* [**17**] | Floor, step 1, and step 2 |
| 5 | Reiner *et al.* [**13**] | Step 3 |
| 7 | Christina and Cavanagh [**7**] | Step 2 and step 4 |
| 9 | Stacoff *et al.* [**9**] | Step 3 and step 4 |

alternatively the patient must repeat the activity with the stairs in a new configuration. This may be unrealistic because of time constraints and patient abilities.

It was hypothesized that different knee kinematics and moments would be produced for different SGCs. Therefore, the aim of the study was to compare the kinematics and moments involved in four different SGCs and thus to determine whether the choice of SGC is an important factor in studies of knee function involving stair gait. This was achieved by evaluating the differences that can exist when GRFs are measured from step 1 and 2 (transition steps) of a four-step staircase. Motion analysis methods and an in-house-designed staircase [**22**] were used to measure and compare non-pathological knee joint kinematics and moments from two different SGCs during stair ascent and descent. The SGCs were chosen to produce different inertial effects when raising and lowering the body's centre of mass (COM) to a greater or lesser extent.

## 2 METHODS

Knee function was evaluated during stair gait for ten subjects (six female and four males; age, 44.9 ± 9.48 years (mean ± standard deviation); height, 1.7 ± 0.09 m (mean ± standard deviation); weight, 76 ± 18.02 kgf (mean ± standard deviation)) with NP knees with no previous injury. Informed consent was given by all subjects and the study was approved by the South East Wales Local Research Ethics Committees. Three-dimensional (3D) motion capture was performed using eight ProReflex MCU digital cameras (Qualisys, Göteborg, Sweden), capturing at 60 Hz. Force data were collected at 1080 Hz from two Bertec force plates (Bertec Corporation, Columbus, Ohio, USA) embedded in the floor of the laboratory. A plate containing a retroreflective marker at each corner was placed on each force plate to define the position of the force plates relative to the global coordinate system (GCS). A previously reported staircase consisting of four independent steps of height 0.16 m and tread 0.28 m was used for this study [**22**] (Fig. 1). A 0.3 m × 0.26 m × 3 mm section was removed from the underside of each of the first two steps. A 6 mm MDF panel of similar dimensions was positioned between either step 1 or step 2 and the force plate to enable force measurements to be recorded during the stance phase of a gait cycle. As the force plates are embedded 2 mm below floor level, this raises the step 1 mm from the ground, ensuring direct measurements from the force plate.

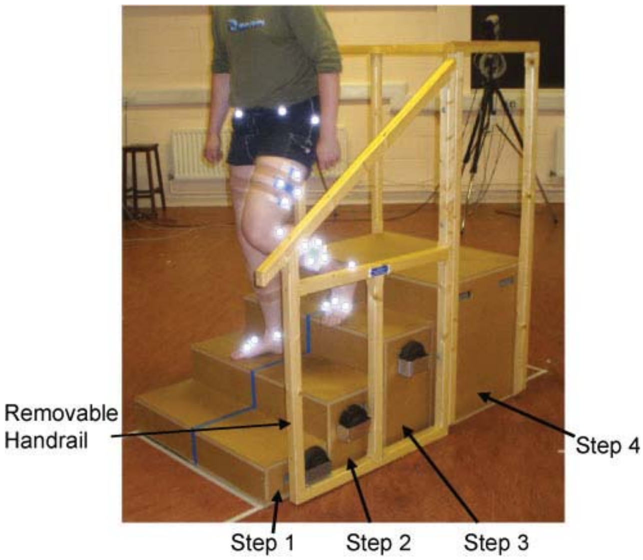


**Fig. 1** Subject descending from step 3 to step 2 of the staircase

A 2.7 kgf counterweight maintained this position (Fig. 2).

Rigid clusters of four retroreflective markers were positioned laterally to the thigh and shank of each subject. Individual markers were positioned on anatomical landmarks in a modified Helen Hayes configuration, as detailed in reference [**21**]. A quiet standing measurement was recorded with the subject's feet a shoulder width apart, for 1 s. The stairs

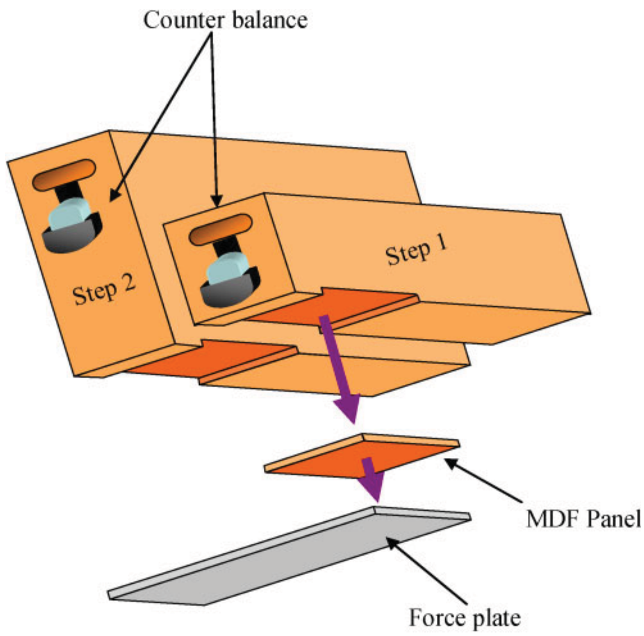


**Fig. 2** Projection from beneath step 1 and step 2 of the staircase, illustrating the interface between each step and a force plate via a medium-density fibreboard (MDF) panel [**22**]

were constructed initially with step 1 in contact with the force plate. The subjects were recorded performing stair ascent, starting with the right leg. A separate measurement was recorded for stair descent, starting with the right leg. This was repeated three times. The staircase was moved forwards so that step 2 was in contact with the force plate. The subjects were recorded performing stair ascent, starting with the left leg. A separate measurement was recorded for stair descent, starting with the left leg. This was also repeated three times. These SGCs ensured that the subject always contacted the step of interest with the right foot. The subjects performed stair ascent and descent without the use of a handrail, although a handrail was present as part of the staircase set-up to comply with laboratory health and safety guidelines. All subjects received the same verbal instructions. A 2 min break was given between each trial, and 5 min between the two test conditions (step 1 and step 2 in contact with the force plate). The mean velocity of stair ascent and descent was 0.48 ($\pm$0.073) m/s.

The following SGCs were selected for analysis:

(a) SGC1 (ascent): right foot strike on step 1 through to right foot strike on step 3;
(b) SGC2 (ascent): right foot strike on step 2 to right foot strike on step 4;
(c) SGC3 (descent): right foot off step 3 to right foot off step 1;
(d) SGC4 (descent): right foot off step 4 to right foot off step 2.

Biomechanical lower-limb models were created for each subject from their static measurements using Visual3D (C-Motion, Inc., Germantown, Maryland, USA) and used for kinematic and kinetic analysis. The pose of each rigidly defined segment was determined by at least three non-collinear points using the vector method. The shank was defined using the position of the epicondyles and malleoli. The thigh was defined using hip joint centre regression [**24**] and the epicondyles. Joint rotations were described by an $X$, $Y$, $Z$ Cardan–Euler sequence, where $Z$ is the positive vertical (upward) axis and $Y$ is positive acting anteriorly. Knee joint moments were computed using inverse dynamic analysis and expressed relative to the laboratory GCS. The moments were expressed as the contribution of the forces to rotate the shank about the knee joint, or 'external moments', and were normalized to body mass. 3D marker coordinates and knee joint moments were filtered using a digital low-pass Butterworth fourth-order filter with a 6 Hz cut-off frequency.

A mean of the kinematic and kinetic waveforms from three trials were computed for each subject. The knee joint range of motion (ROM), peak knee flexion, and peak moments acting about the knee were identified from the mean waveforms. Paired-samples $t$ tests (SPSS 12.0.2) were applied to the kinematic and kinetic measures to compare, first, SGC1 and SGC2 for stair ascent initiated by the stance phase and, second, SGC3 and SGC4 for stair descent ending in the stance phase, to determine significant differences associated with the choice of SGC.

## 3 RESULTS

### 3.1 Kinematics

The mean knee joint kinematic waveforms from the ten subjects and the discrete measures used to compare the SGCs listed in Table 2 are displayed in Fig. 3. A slightly larger rotational ROM was found for SGC2 than for SGC1 in all three planes, but these

**Table 2** Kinematic measures used to compare the different SGCs

| | Variable (deg) | Mean $\pm$ standard deviation ($n = 10$) |
|---|---|---|
| SGC1, ascent, step 1 to step 3 | Flexion–extension ROM | 77.75 $\pm$ 4.30 |
| | Peak flexion angle | 87.67 $\pm$ 5.06 |
| | Adduction–abduction ROM | 10.89 $\pm$ 2.92 |
| | Internal–external ROM | 12.73 $\pm$ 3.51 |
| SGC2, ascent, step 2 to step 4 | Flexion–extension ROM | 80.79 $\pm$ 7.97 |
| | Peak flexion angle | 89.73 $\pm$ 6.59 |
| | Adduction–abduction ROM | 11.25 $\pm$ 2.82 |
| | Internal–external ROM | 13.68 $\pm$ 4.21 |
| SGC3, descent, step 3 to step 1 | Flexion–extension ROM | 80.26 $\pm$ 5.61 |
| | Peak flexion angle | 88.09 $\pm$ 6.56 |
| | Adduction–abduction ROM | 8.87 $\pm$ 1.96 |
| | Internal–external ROM | 11.97 $\pm$ 3.72 |
| SGC4, descent, step 4 to step 2 | Flexion–extension ROM | 80.11 $\pm$ 6.52 |
| | Peak flexion angle | 89.14 $\pm$ 7.87 |
| | Adduction–abduction ROM | 9.89 $\pm$ 1.20 |
| | Internal–external ROM | 13.94 $\pm$ 6.70 |

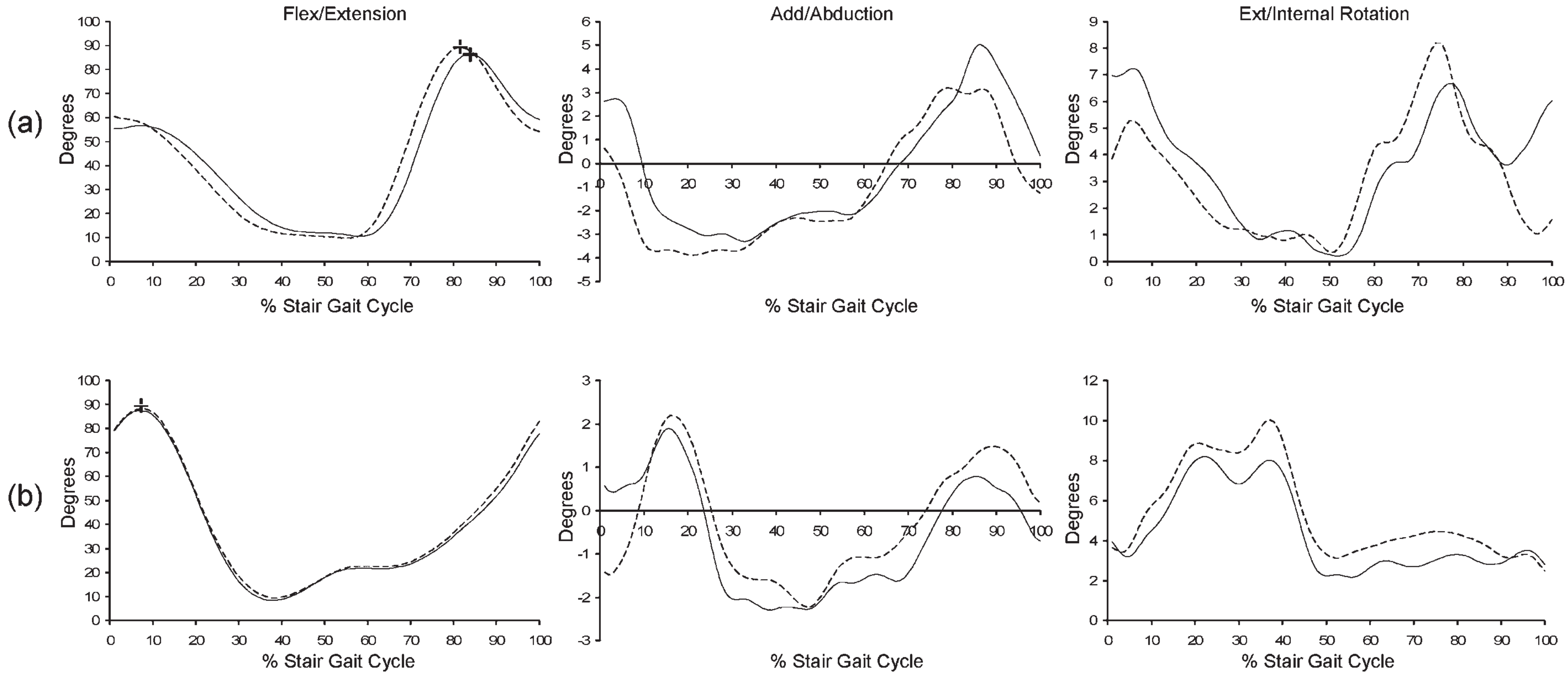


**Fig. 3** Mean knee kinematic waveforms for the two SGCs of (a) stair ascent where the solid curves represent SGC1 and the dashed curves represent SGC2, and (b) stair descent where the solid curves represent SGC3 and the dashed curves represent SGC4: +, peak flexion angle

differences were insignificant. With the exception of the sagittal plane ROM, larger knee rotations were also measured for SGC4 than for SGC3, but the differences were also not significant.

### 3.2 Knee joint moments

The mean knee joint moment profiles and the discrete peak values used for comparison of the SGCs listed in Table 3 are displayed in Fig. 4. Forces were measured from the stance phase on step 1 for SGC1 and SGC3 and on step 2 for SGC2 and SGC4. Larger moments were measured for SGC1 than for SGC2 with the exception of the peak internal rotation moment. The peak adduction moment measured during the stance phase for SGC1 ($0.30 \pm 0.08$ N m/kg) was significantly greater ($p = 0.00$) than for SGC2 ($0.23 \pm 0.09$ N m/kg). For stair descent, larger flexion moments were measured for SGC4, and the second flexion moment peak ($1.17 \pm 0.25$ N m/kg) was significantly larger ($p = 0.016$) than for SGC3 ($0.97 \pm 0.19$ N m/kg). The first mean adduction moment peak for SGC4 ($0.28 \pm 0.15$ Nm/kg) was significantly larger ($p = 0.027$) than for SGC3 ($0.21 \pm 0.18$ Nm/kg). The differences in the remaining measures of knee joint moments for the SGCs of stair descent were not significant.

## 4 DISCUSSION

This study investigated the differences in knee kinematics and moments resulting from analysing different SGCs for ascent and descent. GRFs were measured from step 1 and step 2 of a staircase containing four steps. The SGCs were chosen to assess knee function during the following stages:

(a) the initial pull-up phase where the COM is being raised against gravity (transition phase between floor level and stair gait);
(b) controlled lowering before stepping down to floor level (transition stage between stair gait and floor level);
(c) a cycle collected midstair ascent and descent, which involves greater segmental inertial effects.

Differences in knee kinematics and moments associated with the choice of SGC were quantified using motion analysis methods, and significance was tested using *t* tests.

Larger knee rotations were measured for SGC2 than for SGC1 for ascent, and for SGC4 than for SGC3 for stair descent. These results were not statistically significant. SGC2 is the final gait cycle for ascent (involving the final foot placement on step 4 for stair ascent) and SGC4 is the initial SGC of descent (involving initial toe off step 4 for stair descent). As there is no restriction on foot placement on step 4 at heel strike at the top of the stairs [**1**] and initial toe off as a subject begins stair descent, SGC2 and SGC4 were expected to have significant effects on knee kinematics when compared with SGC1 and SGC3. This study has disproved expectations as the choice of SGC did not significantly affect knee

**Table 3** Measures of knee joint moments used to compare the different SGCs

| | Variable (N m/kg) | Mean ± standard deviation ($n = 10$) |
|---|---|---|
| SGC1, ascent, step 1 (measuring GRFs) to step 3 | Peak flexion moment | $0.86 \pm 0.18$ |
| | Peak extension moment | $0.46 \pm 0.17$ |
| | Peak adduction moment | $0.30 \pm 0.08$* |
| | Peak external rotation moment | $0.07 \pm 0.02$ |
| | Peak internal rotation moment | $0.05 \pm 0.02$ |
| SGC2, ascent, step 2 (measuring GRFs) to step 4 | Peak flexion moment | $0.79 \pm 0.21$ |
| | Peak extension moment | $0.44 \pm 0.11$ |
| | Peak adduction moment | $0.23 \pm 0.09$* |
| | Peak external rotation moment | $0.06 \pm 0.02$ |
| | Peak internal rotation moment | $0.05 \pm 0.02$ |
| SGC3, descent, step 3 to step 1 (measuring GRFs) | First flexion moment peak | $0.57 \pm 0.29$ |
| | Second flexion moment peak | $0.97 \pm 0.19^{\dagger}$ |
| | First adduction moment peak | $0.21 \pm 0.18^{\dagger}$ |
| | Second adduction moment peak | $0.22 \pm 0.17$ |
| | Peak external rotation moment | $0.13 \pm 0.04$ |
| | Peak internal rotation moment | $0.02 \pm 0.02$ |
| SGC4, descent, step 4 to step 2 (measuring GRFs) | First flexion moment peak | $0.60 \pm 0.34$ |
| | Second flexion moment peak | $1.17 \pm 0.25^{\dagger}$ |
| | First adduction moment peak | $0.28 \pm 0.15^{\dagger}$ |
| | Second adduction moment peak | $0.21 \pm 0.13$ |
| | Peak external rotation moment | $0.11 \pm 0.02$ |
| | Peak internal rotation moment | $0.02 \pm 0.01$ |

*Statistical significance ($p < 0.05$) between SGC1 and SGC2.
$^{\dagger}$Statistical significance ($p < 0.05$) between SGC3 and SGC4.

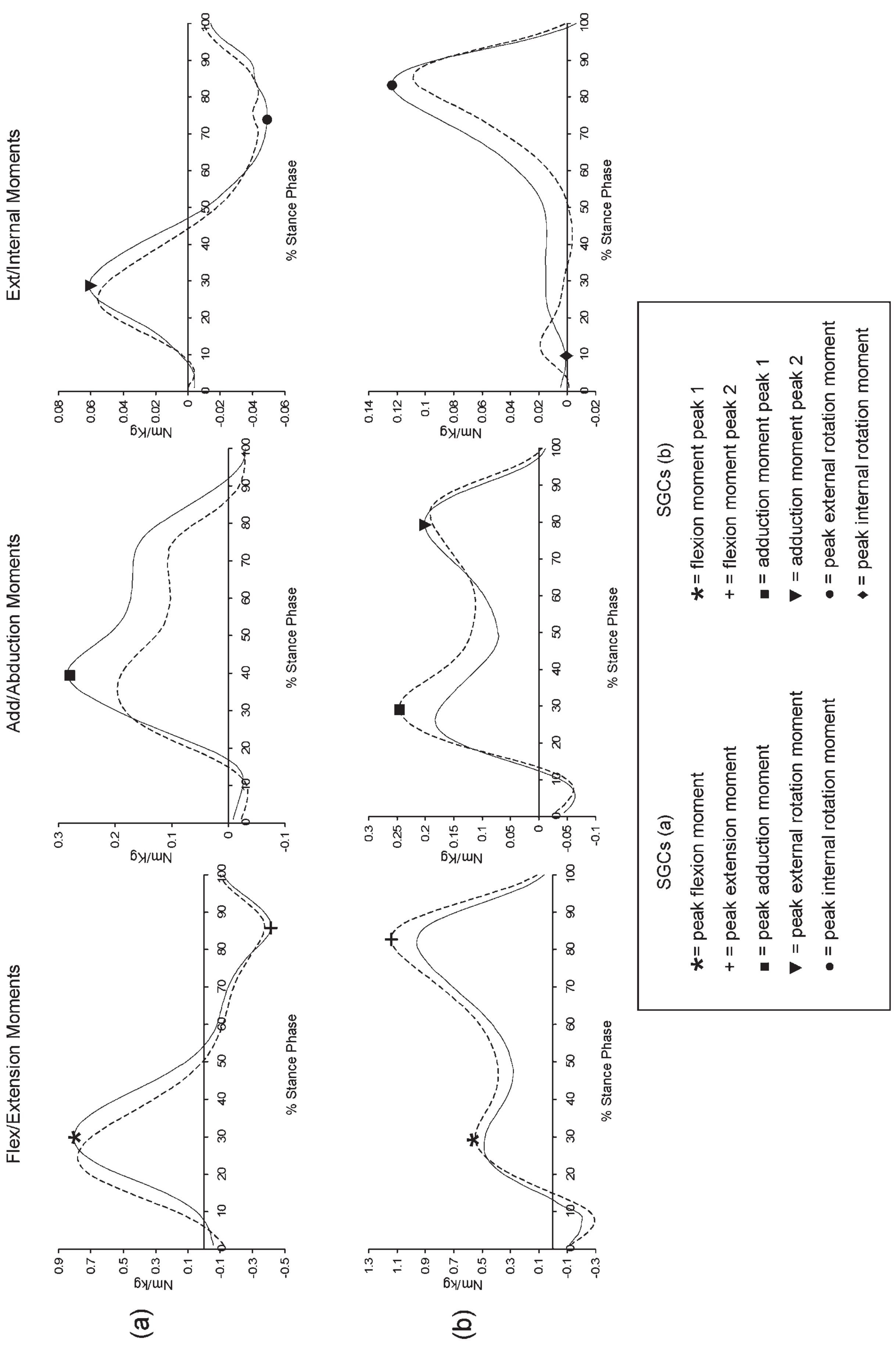


**Fig. 4** Mean knee joint moment waveforms for the two SGCs of (a) stair ascent where the solid curves represent SGC1 and the dashed curves represent SGC2, and (b) stair descent where the solid curves represent SGC3 and the dashed curves represent SGC4. The keys for (a) and (b) list the discrete values used to compare the SGCs

kinematics. The rotational waveforms are more consistent in the sagittal plane. Movement in this plane is likely to be standardized by the consistent step height. The choice of SGC appears to have a greater affect on the smaller transverse and frontal plane rotations, indicating that this is where the majority of the adaptations occur.

The mean peak adduction moment for ascent was significantly larger for SGC1 (measured from the stance phase on step 1) than for SGC2 (measured from the stance phase on step 2). The larger adduction moment occurs during the initial pull-up phase of stair ascent before steady state has been achieved, and thus mechanisms to initiate momentum up the staircase, such as trunk inclination, involves a greater adduction moment at the knee than for foot strike on step 2.

The second mean flexion moment peak was larger for SGC4 where moments are computed from GRF measurements from step 2 than for SGC3 where they are computed from step 1. The lower moment measured during SGC3 may be explained by the fact that both feet are descending to floor level, whereas for SGC4 the limb in stance will progress to the next step below. A higher flexion moment was also reported by Kowalk *et al.* [**3**] for descent from step 2 than for descent from step 1, although their results were not significant. This trend was seen by Andriacchi *et al.* [**2**], where the maximum flexion knee moment occurred during step-to-step gait for stair descent, i.e. an SGC from step 3 to step 1 (where the moments were computed from the stance phase in step 1) compared with an SGC from step 2 to floor level (where the moments were computed from the stance phase on the floor). Thus, considering the findings from these and the current study, it can be concluded that the flexion moment acting at the knee is less for the lowest step of a staircase than for step 2 and that this is reduced further for foot strike on the ground level. The difference in flexion moment from each descending step for full-height staircases is beyond the scope of this study.

A significantly larger first mean adduction moment peak was recorded for SGC4 (descending from step 4 to step 2) than for SGC3 (descending from step 3 to step 1); thus the frontal plane moments are affected by the choice of SGC for descent. This indicates that the knee has different levels of frontal plane stabilization for each SGC of descent. SGC4 involves the initial foot strike of stair descent for the leg under investigation. This initial progression produces an increased adduction moment at the knee. This may be because the body position moves the COM away from the knee joint centre for this portion of stair ascent, as the body moves towards the opposite leg in preparation for foot strike. The frontal plane control appears to be greater for SGC3 where the knee is performing controlled lowering to floor level, with the loaded leg in stance phase on the lowest step 1.

This study has highlighted three significant differences in knee moments resulting from the choice of SGC and step from which to measure GRFs from a four-step staircase. It has shown that, for ascent, the peak frontal moment is significantly larger during the transition from floor level to step 1 than during the transition from floor level to step 2 and, for descent, the sagittal plane and frontal plane moments are significantly larger during the transition from step 2 to floor level than during the transition from step 1 to floor level. This has implications when planning an experimental protocol and when direct comparisons are made between studies using different protocols. This also has implications for clinical assessments where patients have different stair-climbing techniques. A wide variety of limb configurations are mechanically feasible during stair ascent and descent [**25**] and the difference in SGCs may have a greater influence when assessing subjects with joint pathology. The stair ascent and descent SGCs considered in this study involve different mechanisms to raise and lower the body COM to a greater or lesser extent, with various inertial effects. SGC1 involves initial pull-up from a stationary position at floor level, SCG2 involves steady state climbing, SGC3 involves initial lowering from a stationary position on step 4, and SGC4 involves steady state descent prior to stepping to ground level.

It is important to be aware of the differences in knee joint moments that can be obtained as a result of the choice of SGC. This study indicates that the choice of SGC and step used to measure GRFs should be important considerations in future studies including stair gait. The investigation of hip and ankle biomechanics would be useful to gain an appreciation of the alterations at each joint during different cycles of stair ascent and descent and will be investigated in future work.

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