Relationships between performance and kinematic/kinetic variables of stair descent in patients with medial knee osteoarthritis: An evaluation of dynamic stability using an extrapolated center of mass

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Abstract

Background: The ability to descend stairs independently is impaired from a relatively early stage in patients with knee osteoarthritis. The purpose of this study was to evaluate the performance in patients with knee osteoarthritis when stepping down a step by evaluating the dynamic stability using the extrapolated center of mass.

Methods: Twenty-three individuals with medial knee osteoarthritis were evaluated during step descent without any assistance. Kinematic/kinetic data were collected using a three-dimensional motion analysis system and force platforms. The extrapolated center of mass and its deviation from the anterior boundary on the base of support (margin of stability) were calculated at the initiation of descent. Joint angles and internal joint moments were collected at the stance limb. The relationship between patients' dynamic stability control, which was measured by the timed up and go test, and the length of margin of stability were analyzed. Relationships between the length of the margin of stability and each kinematic/kinetic variable were also evaluated

Findings: The margin of stability positively correlated with the time taken for a timed up and go test. A positive correlation was additionally observed between the ankle dorsiflexion angle and the margin of stability. It was also found that a higher ratio of ankle plantar flexion moment by support moment was associated with a larger margin of stability.

Interpretation: Patients with knee osteoarthritis who had high ability in dynamic stability control were observed to move their center of mass anteriorly at the initiation of stepping down. It was also suggested that these patients could dorsiflex their ankle joint and generate sufficient ankle plantar flexor torque.

1. Introduction

Knee osteoarthritis (knee OA) is one of the most common lower extremity diseases in the elderly [1, 2] known to cause pain, joint stiffness, and limitations in activities of daily living [3–5]. The ability to independently negotiate stairs is frequently required in daily living. However, this ability, particularly the action of descending stairs, is easily impaired to the extent that many patients with knee OA are unable to ascend or descend stairs without any assistance, even if these patients' conditions are not severe enough to indicate surgery. Previous studies have described that patients with knee OA demonstrated a slower stair descent than their healthy elderly counterparts [6] and patients gradually developed difficulties in stair decent with disease progression [7, 8]. It was also reported that knee OA patients who underwent knee replacement could not completely recover from their abnormality in descending stairs, such as a decrease in descent speed [9] and the use of a handrail [10], even several months after surgery. Based on these studies, it was supposed that the decline in the ability to descend stairs caused by knee OA would limit mobility independence in the long term. In addition, 10% of falls in the elderly happen during stair negotiation [11], which also indicates that changes in the method used to descend stairs caused by a decline in physical function could lead to an increased risk of falling. Although it was expected that stair descending would influence mobility independence and risk of falls, few studies have investigated the performance of stair descending in patients with knee OA by analyzing their motions. Moreover, while some previous studies have investigated the time-spatial variables in stair descent in patients with knee OA [9], further analysis is needed to consider the lower extremity joint mechanics during stair descent.

It is characteristic of the mechanics in descending steps that much more muscle force, which regulates the anterior-inferior rotation of the body caused by gravity, is required compared to level walking. Therefore, we considered that a quantitative evaluation of dynamic stability during the regulation of the anterior-inferior rotation of the body in stair descent would be valuable in clarifying the features in stair descent in patients with knee OA. In recent studies, dynamic stabilities in some locomotor activities, such as level walking, have been estimated by calculating the extrapolated center of mass (XcoM), which is a concept based on an inverted pendulum model [12]. XcoM is obtained from the anterior-posterior position and the forward velocity of the center of mass (CoM). Dynamic stability in locomotor activities is evaluated by observing Margin of Stability (MoS), which represents the instantaneous distance between the XcoM and the anterior boundary of the base of support (BoS) [13, 14]. One previous study used this method to evaluate dynamic stability while patients descended stairs and disclosed that older individuals showed reduced dynamic stability control compared with young individuals [15]. In patients with knee OA, the condition is also likely to alter their control strategies during stair descent because of such impairments as joint stiffness and muscle weakness, which are caused by their pathology. However, no study has evaluated performance of stair descent in patients with knee OA with regards to dynamic stability using the MoS calculated from XcoM as a measure, and the variables (e.g., joint angle and internal joint moment) associated with this performance are unclear.

The purpose of this study was to evaluate the performance in terms of dynamic stability while stepping down stairs in patients with knee OA through observation of XcoM and MoS behavior. We hypothesized that performance in descending a step is associated not with knee joint kinematics/kinetics but with other joints kinematics/kinetics because the hip/ankle joint would compensate for their failure of joint angular displacement or torque generation at the knee in patients with knee OA.

2. Methods

2.1 Participants

Twenty-three individuals with medial knee OA diagnosed by an orthopedic surgeon were recruited for this study. Patients with other types of arthritis (e.g., lateral knee OA, rheumatoid arthritis) or those who had undergone previous surgery in the lower extremities were excluded. Patients diagnosed with any other disease that could affect ambulation were also excluded from the study. All participants were able to descend at least one step without any assistance. Following Institutional Review Board approval, written informed consent was obtained from each participant before the study began.

While only the affected limb was analyzed in this study, the more symptomatic side of each patient was involved if patients had bilateral knee OA. The radiographic severity of each patient was determined using Kellgren-Lawrence classification by an experienced orthopedic surgeon. The disease-specific scale of the Japanese Knee Osteoarthritis Measure (JKOM) was used to evaluate their symptoms and physical functions. The JKOM is a self-administered measure consisting of 25 items, which include subjective pain in level walking, standing, or climbing stairs as well as physical functions related to the activities of daily living and social functions. The maximum score for the JKOM is 100 points, and higher scores indicate more impaired function. Pain in daily living was also quantified by using the visual analog scale (VAS). The participants' demographic characteristics are shown in Table 1.

2.2 Measure of functional balance ability

To evaluate each participant's ambulation and functional balance ability, the timed up and go test (TUG) was used. In this test, participants initially sat on a chair with a seat height of 42 cm. Each participant was instructed to stand up, walk toward a mark, which had been placed 3 m from the starting position, turn around, walk back to the chair, and sit down again. They were also asked to perform this sequence of activities as fast as possible. Each participant completed the trials twice, and the time taken to complete the test was recorded. The faster of the two trials was used for analysis.

2.3 Motion capture of descending a step

All participants performed three trials of stepping one step down. The step riser height and tread width were 20 and 40 cm, respectively (Fig. 1). They were asked to descend at a self-selected speed and to lead with the uninvolved limb. In order to standardize the step length between participants, each trial began with the subjects standing with both toes against the anterior edge of the step. They were instructed not to cross their toes over a line that was drawn 25 cm from the edge of the step when they descended toward the lower step. Both arms were folded in front of their abdomen in an attempt to standardize the effects of motion of the upper extremities on their ambulation. Before the sampled trials, each participant completed a couple of trials for familiarization.

Kinematic and kinetic data were obtained using a three-dimensional motion analysis system

(Vicon Nexus; Vicon Motion Systems Ltd., Oxford, UK) and force platforms (Kistler Japan Co., Tokyo, Japan). The step was placed upon the platform, and ground reaction force data were collected during the trials. The sampling frequency of the motion analysis system and force platforms were 200 Hz and 1000 Hz, respectively, and these two were synchronized during the analysis. Thirty reflective markers were placed on the following bony landmarks by a single examiner: the spinous process of the seventh cervical vertebra and the tenth thoracic vertebra, suprasternal notch, xiphoid process, bilateral acromioclavicular joints, lateral humeral epicondyle, styloid process of the radius, anterior superior iliac spine, posterior superior iliac spine, superior aspect of the greater trochanter, lateral and medial femoral epicondyle, lateral and medial malleolus, first and fifth metatarsal heads, and calcaneus. The hip joint center was determined by first calculating a vector linking the reflective markers attached at both greater trochanters. Then, the hip joint center was identified as the interpolated point located at a distance of 18% of the vector norm from each marker attached at the superior aspect of the greater trochanter along the vector. The knee joint center was determined as the mid-point between two markers located at the lateral and medial femoral epicondyles. The ankle joint center was located at the mid-point between the lateral and medial malleolus [16].

The Vicon Bodybuilder (Vicon Nexus; Vicon Motion Systems Ltd., Oxford, UK) application was used for calculating the position of the CoM with respect to laboratory coordinates. Joint angles and internal moments in the sagittal plane were also calculated at the hip, knee, and ankle of the involved limb. The internal joint moments were determined by using inverse dynamics. Before these calculations, displacement of each marker was filtered using a fourth-order Butterworth low-pass filter with a 6-Hz cutoff. The moment of inertia was determined as in previous study described by Winter et al. [17]. All kinetic data were low-pass filtered with a 25-Hz cutoff and normalized for body weight and height.

2.4 Data analysis

Using the data of CoM displacement, XcoM values were determined as follows:

$$\text{XcoM} = \text{pCoM} + \frac{vCOM}{\sqrt{gl^{-1}}} ,$$

where pCoM is the anterior-posterior position of the CoM, which was projected to the ground, vCoM denotes the anterior-posterior velocity of the CoM, g is the acceleration of gravity, and l is the distance between the CoM and the center of the ankle joint (Fig. 1). XcoM is the estimated CoM position which represents the position that the CoM would reach to during dynamic movement and is calculated by adding the anterior-posterior velocity of CoM divided by the eigenfrequency of the inverted pendulum to the temporary position of the CoM. The margin of stability (MoS), which was used as the variable representing the performance of stair descent in subsequent analysis, was defined as the distance between the XcoM and the anterior boundary of the BoS, which was approximated as the anterior edge of the step in this study. As the position of the CoM is within the BoS while postural stability is sustained, an increase in MoS indicates that the XcoM exceeds the BoS and stability is therefore disturbed [12]. The waveforms of MoS and internal joint moment at each joint during stepping down a stair for one representative patient are described in Figure 2.

For subsequent analysis, a value for the MoS was obtained at the time when a marker placed on the heel of the uninvolved limb descended beneath the edge of the step (i.e., when the vertical height of the marker became less than 20 cm with respect to laboratory coordinates). Variables of each joint angle and internal joint moment were also sampled at the same time to clarify which joint kinematic/kinetic variables were most associated with the performance of stair descent in these patients. Further, a value for the support moment, which was defined as the summation of hip extension, knee extension, and ankle plantar flexion moments [18], was obtained, and the proportions of each joint moment to each support moment were calculated. This timing was chosen for analysis because patients' motion at this timing was easily observed visually even in the clinical setting. In addition, the timing was chosen because the body would move in accordance with the inverted pendulum model immediately after the initiation of the descent movement, while CoM continues to drop during stair descent (i.e. the CoM movement would gradually deviate from the inverted pendulum model).

It was also selected because controlling anterior-inferior rotation of the body at this timing, when the swing limb started going down toward the lower step, requires much energy to be generated by the stance (involved) limb.

2.5 Statistical analysis

For each kinematic and kinetic variable, the averaged values of the three trials were used for subsequent statistical analysis. First, Pearson correlation coefficient was calculated between the time taken for TUG and MoS to evaluate the relationship between the MoS and each patient's functional balance ability. Furthermore, the relationships between the joint angle and internal joint moment at each joint and the MoS were assessed using the same correlation coefficients. Spearman rank correlation coefficients were also calculated between the MoS and the proportions of each joint moment by support moment. The significance level was set at 5%. IBM SPSS statistics 20.0 was used for the statistical analysis.

3. Results

The mean time taken for the TUG test was 6.83 sec (Table 2). Kinematic and kinetic variables including MoS, anterior-posterior position and velocity of CoM, joint angles, internal joint moments, and the proportions of each joint moment by support moment are shown in Table 3. MoS was positively correlated with the time taken for TUG and was significant ($r = -0.42$, $p < 0.05$, Table 2 and Fig. 2). For the joint angles and internal joint moments, a positive correlation was observed between the ankle dorsiflexion angle and the MoS ($r = 0.44$, $p < 0.05$), while hip extension moment was negatively correlated with MoS ($r = -0.57$, $p < 0.01$). It was also found that a higher ratio of ankle plantar flexion moment ($r = 0.54$, $p < 0.01$) and a lower ratio of hip extension moment ($r = -0.48$, $p < 0.05$) to support moment were both associated with a larger MoS.

4. Discussion

Although patients with knee OA experience a decline in their ability to negotiate stairs, especially descending stairs, no study has investigated their performance quantitatively. Therefore, we attempted to assess patients' performance in stepping down by evaluating the XcoM and MoS, which has been used to quantify dynamic stability in previous studies. Furthermore, this study also aimed to investigate which variables (i.e., joint angular displacement and internal torque exertion at each joint in the lower extremity) affected the stair descent performance. As a result, it was suggested that dynamic stability control during stepping down was associated with angular displacement and internal torque generation not at the knee but mainly at the ankle joint, which supported our hypothesis.

We presumed that it is reasonable to evaluate the dynamic stability to quantify patients' performance because control of the anterior-inferior rotation of their body caused by gravity is required when descending stairs. Therefore, the MoS, which indicates the magnitude of the deviation between XcoM and BoS, was calculated for each patient with knee OA to evaluate their dynamic stability while descending a step. Although XcoM, which is based on the inverted pendulum model, is the estimated position of the center of the body mass, movement during stair ambulation does not always accord with this model. In terms of stair descent, the distance between the CoM and the ankle joint center is gradually shortened as the body descends toward the lower step (i.e., l is gradually shortened). Therefore, the XcoM calculated in this study might be overestimated compared to the actual location in which the CoM was moving, which was also mentioned in a previous study that investigated XcoM during stair descent [15]. It was, however, assumed that this would have little or no impact on the results in the study because the timing at which the XcoM was collected in this study was almost simultaneous with the initiation of stepping down, when anterior inclination and lower displacement of patient's body were very limited.

The results of this study showed that patients who performed the TUG test quickly could descend a step with a larger MoS. Since the TUG test includes the motions of walking, changing direction, standing, and sitting, the time taken for the TUG test is commonly used as an evaluation of ambulation ability [19]. Subjects who could perform the TUG test rapidly were acknowledged to have high ambulation ability. While the TUG test is also used for evaluating functional balance in general, we applied this test to patients with knee OA in an attempt to clarify the relationship between the functional balance ability (dynamic stability control in activities of daily living) and MoS during stair descent. Several previous studies have disclosed that if the XcoM exceeds BoS (which would be equivalent to the MoS becoming larger in this study), the body might be unstable [20], which could induce falling. On the other hand, when a subject initiates any kind of ambulation, CoM needs to exceed BoS [21]. Therefore, it was assumed that patients with high ability in dynamic stability control could increase their MoS more than patients with low dynamic stability control at initiation of stair ambulation. In this study, the timing when the heel of the uninvolved limb descended lower than the edge of step, that is when the swing limb started moving towards the lower step, was chosen for analysis. As patients descended only one step in this study, which is unlike stair negotiation encountered in daily living, the timing mentioned above was close to the initiation of ambulation. Patients with high dynamic stability control were observed to start descending with a larger MoS.

With regard to kinematic variables, larger MoS values were observed in patients who started stepping down with a larger ankle dorsiflexion angle. This trend indicated that ankle dorsiflexion contributed to moving patients' CoM anteriorly. As a previous study disclosed that patients with knee OA demonstrated later ankle dorsiflexion during the support phase of stair descent than their healthy elderly counterparts [22], it is thought that some type of relationship exists between ankle dorsiflexion during stair descent and difficulties with stair negotiation in these patients. Patients with knee OA, who are widely known to have impaired knee extensor muscle function [23, 24] and to descend stairs with a limited knee flexion angle [7, 22], were required to further flex other joints in the lower extremity in order to displace their CoM anterior-inferiorly. Consequently, patients who could move their CoM anteriorly when they initiated stair descent, those who had high dynamic stability control, were expected to descend the step with a larger ankle dorsiflexion angle. In contrast, patients who had an inferior ability for stair descent could not move their CoM anteriorly due to the decrease in the ankle dorsiflexion angle. Although the performance of stair descent is generally thought to be affected by pain in patients with knee OA, patients included in this study did not have severe pain (the mean VAS score in daily activities was 29 mm) that could have affected their movement in each trial.

The results also indicated several relationships between the length of the MoS and several kinetic variables. Larger MoS values were associated with a higher ratio of internal ankle plantar flexion moment to support moment, while a higher hip extension moment and its ratio to support moment had an opposite relationship with MoS. According to these results, patients with high ability in dynamic stability control were assumed to initiate stepping down with greater ankle plantar flexion torque. Based on a previous study, which clarified the association between the magnitude of internal ankle plantar flexor torque and anterior velocity of the CoM during stair descent in healthy elderly participants [15], it was suggested that greater ankle extensor torque was associated with MoS, which is calculated using the anterior velocity. Since the support moment was not significantly correlated with the length of the MoS in this study (r = 0.34, p = 0.108), patients who could perform a stair descent smoothly generated a relatively large amount of ankle plantar flexor torque regardless of how much gross amount of leg extensor torque was generated. Regarding the negative correlation between internal hip extension torque and MoS, patients who did not generate enough extensor torque at the ankle joint, that is, those who did not displace their CoM anteriorly enough, were presumed to compensate for the shortage of support moment with hip extensor torque to support their body weight.

There were some limitations to this study; first, this study only included patients with knee OA. Further investigation will be required because this study did not compare these kinematic kinetic variables with healthy, age-matched subjects and hence cannot conclude that the changes in movement were derived solely from knee OA. Another limitation was that the task in this study was a simulated step down, which is not quite the same as the type of stair descent that patients encounter in daily living. However, this study used stepping down for motion analysis because not all of our patients could descend stairs without using a handrail; therefore, we could not use actual stairs for safety reasons. Finally, we evaluated the participants' stair descent performance by analyzing the correlation between the length of MoS and time taken for the TUG test. This test, which is commonly used to evaluate abilities in ambulation and functional balance, was applied to patients in order to measure their performance during stepping down. However, since the TUG test does not include stair ambulation as one of its tasks, the application of this test for evaluating the ability of stair ambulation has not been defined. Further study that uses a measurement to evaluate patients' ability will likely be required with a particular focus on stair ambulation.

5. Conclusion

This study aimed to evaluate the performance of stair descent, an activity that is difficult for patients with knee OA, by using the XcoM and MoS, which express the dynamic stability in ambulation. The results showed that patients with high dynamic stability control were able to move their XcoM more anteriorly at the initiation of step down, and these patients were observed to descend a step with a larger ankle dorsiflexion angle and more ankle plantar flexor torque. The findings in this study will contribute to movement modification or exercise prescriptions for patients who experience an impaired ability of stair negotiation.

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Figure Legends

Figure 1. Evaluation of dynamic stability during stepping down with XcoM, pCoM: anterior-posterior position of CoM, vCoM: the anterior-posterior velocity of CoM, g: acceleration of gravity (9.8 m/s^2), l: the distance between the CoM and the center of the ankle joint, XcoM: extrapolated center of mass, MoS: margin of stability

Figure 2. The representative waveform (n=1) of MoS (black line), internal hip extension moment (gray solid line), internal knee extension moment (gray dashed line), internal ankle planter flexion moment (gray dotted line). The red line drawn in this graph represents the time point chosen for analysis.

Figure 3. The relationship between the time taken for TUG and MoS at the initiation of stepping down for all participants ($r = -0.42$, $p < 0.05$)

Figure 1.

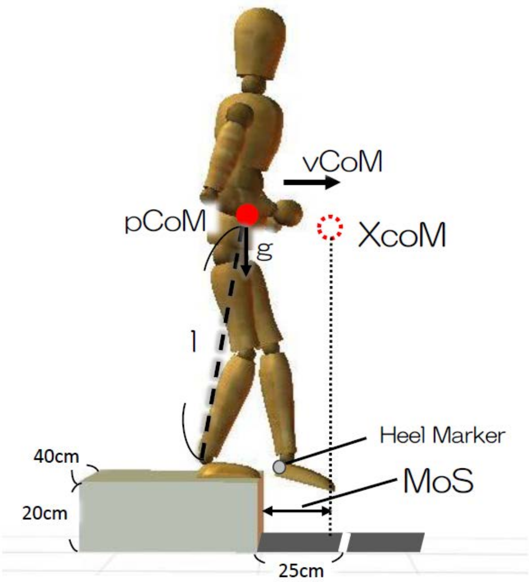
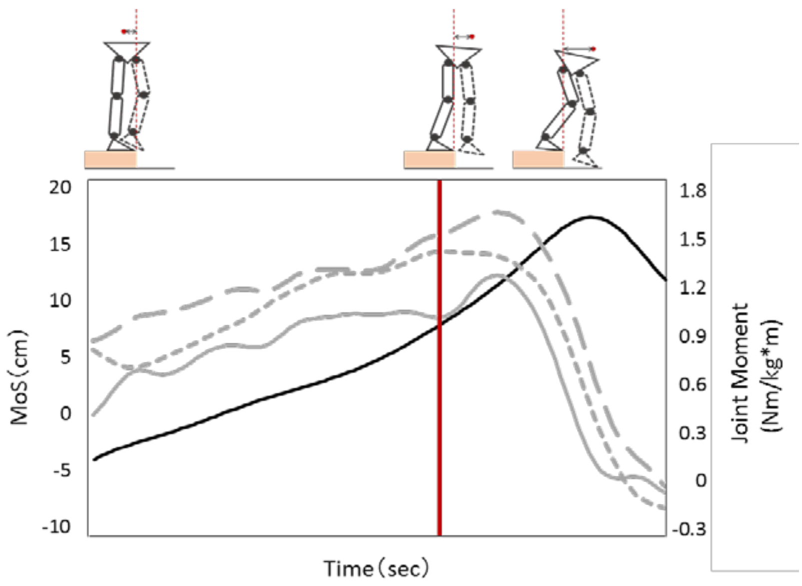


Figure 2.



20
15
10
5
0
-5
-10
MoS (cm)
1.8
1.5
1.2
0.9
0.6
0.3
0
-0.3
Joint Moment
(Nm/kg*m)
Time (sec)

Figure 3.

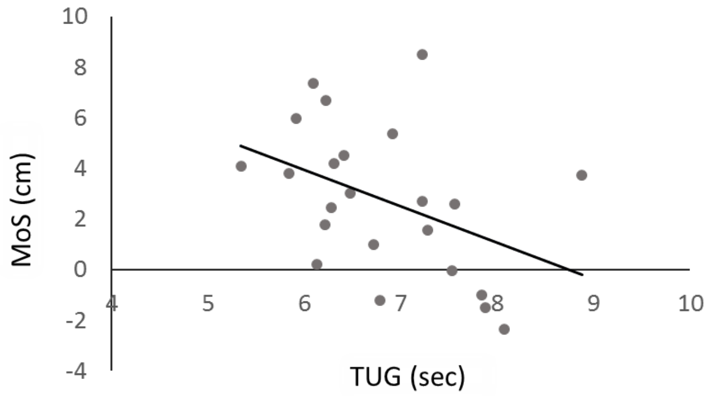


Table 1. Demographic characteristics of the participants, mean (standard deviation)

Age (years)	66.7 (8.5)
Height (cm)	156.5 (4.7)
Weight (kg)	59.8 (6.8)
KL grade	I: 2 II: 13 III: 4 IV: 4
FTA (deg)	180.4 (4.3)
VAS (mm)	29 (21)
JKOM score	19.1 (13.1)

KL grade: Kellgren-Lawrence grade, FTA: femorotibial angle, VAS: visual analog scale
JKOM: Japanese Knee Osteoarthritis Measure

Table 2. Mean value (standard deviation) of the time taken for TUG and its correlation to MoS

TUG (sec)	6.83 (0.86)
Correlation coefficient to MoS	r = -0.42*

TUG: timed up and go test, MoS: margin of stability

* Correlation is significant at $p < 0.05$

Table 3. Mean values (standard deviation) of MoS, pCoM, vCoM, and lower joint kinematic/kinetic variables

MoS, pCoM, vCoM	
MoS (cm)	2.8 (2.9)
pCoM (cm)	-2.6 (1.9)
vCoM (m/sec)	0.21 (0.04)
Joint angle (deg)	
Hip flexion	22.7 (8.73)
Knee flexion	36.6 (4.2)
Ankle dorsiflexion	23.0 (3.7)
Internal joint moment (Nm/kg*m)	
Hip extension	0.18 (0.39)
Knee extension	0.99 (0.23)
Ankle plantar flexion	1.34 (0.24)
Proportions to support moment (%)	
Hip extension	5.7 (18.5)
Knee extension	40.5 (13.4)
Ankle plantar flexion	53.8 (9.9)

MoS: margin of stability, pCoM: anterior-posterior position of center of mass, vCOM: anterior-posterior velocity of center of mass

Table 4. Correlations between each kinematic/kinetic variable and MoS during stepping down

Joint angle	
Hip flexion	0.16
Knee flexion	0.15
Ankle dorsiflexion	0.44*
Internal joint moment	
Hip extension	-0.57**
Knee extension	-0.20
Ankle plantar flexion	-0.28
Proportions to support moment	
Hip extension	-0.48*
Knee extension	0.16
Ankle plantar flexion	0.54**

Values denote Pearson or Spearman coefficients

*Correlation is significant at $p < 0.05$ ** Correlation is significant at $p < 0.01$

Highlights

- We evaluated dynamic stability control during stepping down in patients with knee osteoarthritis.
- The degree of dynamic stability control was quantified by calculating the extrapolated center of mass.
- Patients with high dynamic stability control were able to move their extrapolated center of mass more anteriorly at the initiation of step down.
- Adequate ankle joint dorsiflexion and plantar flexor torque generation would improve the performance during stair descent in patients with knee osteoarthritis.