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Hip and trunk biomechanics and dynamic balance during steady-state stair walking in people with mild-to-moderate hip osteoarthritis

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ABSTRACT

Stair walking is more demanding than level walking, and differences have been found between steady-state stair walking and gait-to-stair or stair-to-gait transition. However, there is limited knowledge on steady-state stair walking biomechanics in people with hip osteoarthritis (HOA) as all existing data were obtained during gait-to-stair transition. The aim of the present study was to investigate the effects of mild-to-moderate HOA on hip and trunk biomechanics and dynamic balance during steady-state stair walking.

Hip and trunk biomechanics and dynamic balance during steady-state stair walking were assessed in 21 participants with mild-to-moderate HOA and 21 age-matched healthy controls using an optoelectronic motion capture system and a custom-built instrumented six-step staircase. Dynamic balance was assessed using the inverted pendulum model with an extrapolated centre of mass. Differences between the two groups were analysed with an independent *t*-test either on discrete parameters or on entire time curves using statistical parametric mapping.

The HOA group showed longer stride and stance phase durations during stair ascent and descent, and lower peak vertical CoM acceleration during stair descent vs. the control group. Trunk kinematics did not differ between groups. Lower frontal plane hip range of motion and hip internal rotation moment, but greater anterior margin of stability were observed during stair ascent in the HOA vs. control group.

Mild-to-moderate HOA reduced frontal hip mobility but did not affect mediolateral dynamic balance during steady-state stair walking. Despite a lack of alterations in sagittal hip or trunk kinematics or dynamics, greater anterior margin of stability in HOA vs. control participants showed a more stable but potentially less efficient motion during stair ascent. Lastly, lower vertical acceleration during stair descent might reduce impact and joint loading at initial contact. Future studies should analyse gait efficiency and joint loading, and the effect of HOA severity and muscle force capacity on steady-state stair walking biomechanics in people with HOA.

1. Introduction

Hip osteoarthritis (HOA) is a progressive disease that is very common, especially in the elderly (Dagenais et al., 2009). Of the people aged 45 years or above, 28 % show radiographic signs of HOA and 9.7 % develop symptomatic HOA (Jordan et al., 2009). HOA affects all joint structures (Block & Shakoor, 2009), and causes pain and loss of function (Salaffi et al., 2005). These functional limitations can significantly alter movement patterns and affect mobility. Therefore, a great portion of research on HOA-induced modifications to movement biomechanics has focused on level walking (Steingrebe et al., 2023). However, other everyday tasks, such as stair walking, impose higher demands than level walking, in terms of greater lower limb sagittal and frontal joint angles, hip and knee joint moments (Andriacchi et al., 1980; Nadeau et al., 2003; Riener et al., 2002), and hip joint contact forces (Bergmann et al., 2001). Previous studies have found lower movement velocity and higher stance duration during stair ascent and descent, and lower cadence and higher double-support time during stair descent in people with moderate-to-severe HOA compared to healthy controls (Hall et al., 2017; Meyer et al., 2016). During stair ascent, people with varying degrees of HOA showed lower peak hip angles and range of motion (RoM) in all directions and planes compared to healthy controls (Hall et al.,

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Table 1
Participant inclusion and exclusion criteria.

Group	Inclusion criteria	Exclusion criteria
HOA	• K-L-Score of 2–4 • Hip pain during activities of daily living within the last 3 months • Harris Hip Score between 65 and 95 • Contralateral K-L-Score ≤ 2 • Contralateral hip pain free within the last 3 months • Unrestricted passive RoM of contralateral hip (sagittal RoM ≥ 90°; transverse RoM ≥ 15°; peak abduction ≥ 20; flexing contracture ≤ 10°)	• Secondary HOA caused by trauma • Contraindications to radiography • BMI ≥ 35 kg/m^2 • Orthopaedic injury of other joints of the lower limbs and back • Neuromuscular disorders or neurological complaints
Control	• Bilateral K-L-Score ≤ 1 (if radiographic images available) • No hip pain within the last 3 months during activities of daily living • Harris Hip Score ≥ 96	• BMI ≥ 35 kg/m^2 • Orthopaedic injury of the lower limbs and back • Neuromuscular disorders or neurological complaints

HOA = hip osteoarthritis; K-L-Score = Kellgren-Lawrence-Score; BMI = Body Mass Index; RoM = range of motion.

2017; Meyer et al., 2016; Popovic et al., 2021), except for greater peak hip external rotation in people with mild-to-moderate HOA compared to healthy controls (Popovic et al., 2021). Peak hip flexion, abduction and external rotation moments were also found to be lower in people with moderate-to-severe HOA compared to healthy controls during stair ascent (Hall et al., 2017; Meyer et al., 2016). During stair descent, people with moderate-to-severe HOA demonstrated lower sagittal hip RoM, peak hip extension and external rotation moment, but greater ipsilateral trunk lean compared to healthy controls (Hall et al., 2017).

However, these studies used staircases with only one or two steps (Hall et al., 2017; Meyer et al., 2016) or analysed the biomechanics on the first or last step (Popovic et al., 2021). Lower body kinematics of transition steps from level walking to stair walking or vice versa differ from those during steady-state level or stair walking. Thereby, larger hip and knee flexion was found in healthy people during steady-state stair walking steps compared to transition steps (Alcock et al., 2014; Andriacchi et al., 1980; Neuman & Fey, 2023). In contrast to transition steps, anteroposterior positioning of the foot is restricted by tread size in steady-state stair walking (Bosse et al., 2012). Therefore, the base of support (BoS) during this task is likely smaller than during the transition, imposing higher demands on dynamic balance and centre of mass (CoM) control (Novak et al., 2016). In static movements, postural stability is assumed if the projection of the CoM falls within the boundaries of the BoS. Yet, this is not always true in movements like walking where the CoM is outside the BoS but postural stability is maintained (Winter, 1995). Consequently, Hof, (2008), Hof et al., (2005) developed the concept of the extrapolated CoM (xCoM), which considers both the position and velocity of the CoM. This concept has been used frequently to quantify balance during dynamic movement tasks including step and stair walking (Bosse et al., 2012; Koyama et al., 2015; Novak et al., 2016). Previous studies employed a variety of balance tests to assess the impact of HOA on balance and have yielded conflicting results: Balance impairments of people with HOA were only found partially when compared to healthy controls or the contralateral limb (Picorelli et al., 2018). Thereby, most studies used static tasks to assess balance, which is not transferable to dynamic balance tasks as balance is task-specific (Ringhof & Stein, 2018).

Therefore, we aimed to investigate steady-state stair walking biomechanics and task-specific dynamic balance in people with mild-to-moderate HOA. We hypothesized that HOA participants would show (I) lower movement velocity; (II) lower peak hip flexion angle and anterior trunk lean, increasing anteroposterior dynamic stability; (III) lower hip adduction angle but greater hip abduction angle, hip external rotation angle and ipsilateral trunk lean, increasing mediolateral dynamic stability; and (IV) lower external hip joint moments in all movement planes.

2. Methods

Data for this case-control study was collected in the biomechanics laboratory of the Institute of Sports and Sports Science of the Karlsruhe Institute of Technology (Germany) between April 2019 and March 2021. Participant inclusion and exclusion criteria are listed in Table 1.

2.1. Testing protocol

Participants performed five valid trials (no handrail use, no tripping) of stair ascent and descent at a self-selected speed in a step-over manner. Self-selected movement speed was chosen to capture the natural movement strategies of people with and without HOA. Stair ascent was initiated few steps before the staircase, whereas descent was initiated without approach steps from the top platform.

2.2. Data acquisition

Hip and trunk biomechanics were assessed using a 16-camera infrared motion capturing system (200 Hz; Vicon Motion Systems, Oxford Metrics Group, Oxford, UK) and a custom-built instrumented staircase with six steps (Fig. 1). These had a riser height of 17 cm and a tread of 28 cm (inclination angle 31.26°). Steps four and five were equipped with 3D strain gauges (1000 Hz; ME-Meßsysteme GmbH, Henningsdorf, Germany), while the remaining steps were instrumented with 1D strain gauges for segmentation purposes (1000 Hz; Wii Balance Board, Nintendo, Kyoto, Japan). Participants were equipped with a full-body marker set (42 retroreflective markers; **Fig. S1**; **Table S1**) by the same researcher, and several anthropometric measures were taken for individual scaling of the biomechanical model (**Table S2**).

2.3. Data processing, biomechanical modelling and dependent variables

Postprocessing of data was conducted in Vicon Nexus (version 2.14.0; Vicon Motion Systems, Oxford Metrics Group, Oxford, UK) and Matlab (version R2022a; The MathWorks Inc, Natick, MA, USA). Kinematic and ground reaction force (GRF) data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz (Kristianslund et al., 2012). 3D joint angles and external joint moments of the hip joint, and the CoM, were calculated using an inverse kinematics and dynamics approach with the multi-body model ALASKA Dynamicus (Hermsdorf et al., 2019), including the hip joint centre definition proposed by Harrington (Harrington et al., 2007). Hip joint moments were normalised to body mass. CoM calculation was based on a mathematical model including 20 segments (**Fig. S2**) of homogenous density, scaled using 65 individual anthropometrical measures (**Table S2**). Total CoM was calculated using weighted summation using the previously calculated mass and inertia properties of the segments (Hermsdorf et al., 2019). Sagittal and frontal trunk angle was calculated as the angle between a vector from the midpoint of both anterior superior iliac spine markers to the clavicle marker and the vertical axis. The evaluated gait cycle of the ipsilateral limb for the HOA group or a matched limb for the control group started with initial contact (IC) on

Fig. 1. Picture of the instrumented staircase. Three-dimensional force plates in steps four and five from the bottom, one-dimensional force plates in steps one to three and six. Riser height = 17 cm, tread = 28 cm, inclination angle = 31.26°.

the fourth step and ended with IC on the sixth step for stair ascent, or started with IC on the fifth step and ended with IC on the third step for descent. IC was detected by a vertical GRF > 15 N. The dependent variables were peak 3D hip joint angles and moments, mean vertical and anteroposterior CoM velocity and acceleration, peak sagittal and frontal trunk angles, gait cycle and stance phase duration.

Dynamic balance was assessed using the inverted pendulum model described by Hof et al. (2005) in the anterior, posterior, medial and lateral directions during the single support phase of the gait cycle. Instability in this model is defined as the xCoM being outside the boundaries of the BoS. Thereby, xCoM is defined as the position of the CoM (pCoM) plus its velocity divided by the eigenfrequency of the pendulum, with the pendulum length (l) being defined as the instantaneous distance from the ipsilateral ankle joint centre to the CoM and with g being the acceleration of gravity.

$$xCoM = pCoM + \frac{vCoM}{\sqrt{g/l}}$$

Stability of the system is then expressed by the margin of stability (MoS) which is defined as:

$$MoS = BoS - xCoM$$

Negative MoS values indicate an instantaneous instability of the system, which has to be counteracted, for example, by a change in BoS to prevent falling. Dynamic balance was assessed in the sagittal and frontal planes. The outer edge of the BoS was defined laterally by the fifth metatarsal marker, medially by the first metatarsal marker, anteriorly by the toe marker and posteriorly by the heel marker. If the foot was not positioned entirely on the tread, the edge of the BoS was defined by the tread edge (Novak et al., 2016). Minimum and maximum MoS during the single-support phase in each direction were used as dependent variables.

All parameters were averaged across five valid trials of each movement. Angle, moment and MoS time curves were time-normalised to 100 % of the gait cycle, stance phase and single-support phase, respectively.

2.4. Statistical analysis

Statistical analyses of discrete parameters were performed in R (version 4.2.2; R Core Team, 2023) and the rstatix, effsize, psych and stats packages. Normal distribution and homogeneity of variance were assessed using Shapiro-Wilk and Levene's tests, respectively. Differences between groups were assessed using independent sample t-tests or Mann-Whitney-U tests. In a secondary analysis, group comparisons were verified using an ANCOVA with leg length as a covariate. Since no discrepancies were found, *t*-test results are presented in the results section. The level of significance was set *a priori* to $p < 0.05$. Cohen's d (Cohen, 1988) was used to calculate effect sizes for all group comparisons. Additionally, continuous angle, moment and MoS time curves were compared using statistical parametric (SPM) or nonparametric mapping (SnPM) (Pataky, 2010). To calculate SPM on observed time series, one trial of each participant was selected based on the lowest root mean square error to the average time curve across all five trials. SPM analyses were implemented using the open-source spm1d code (version M.0.4.10; spm1d.org) in Matlab (version R2022a; The MathWorks Inc, Natick, MA, USA).

2.5. Ethics

The study procedure was approved by the ethical committee of the Karlsruhe Institute of Technology. All participants gave written informed consent for study participation and publication of anonymized results before study participation

3. Results

In total, 42 individuals participated in this study: 21 with symptomatic mild-to-moderate HOA and 21 without HOA. Table 2 provides detailed participant characteristics for both groups**.** The HOA and control groups did not differ regarding age ($p = 0.769$), body mass ($p = 0.429$), height ($p = 0.981$), BMI ($p = 0.257$) or functional leg length ($p = 0.748$).

Tables 3 and 4 show descriptive data for all analysed parameters for stair ascent and descent, respectively. Figs. 2 to 5 present results of time curve analyses for hip joint angles and moments. The **Supplementary Material** (**Figs. S3-S6**) contains results of time curve analyses for trunk angles and MoS.

3.1. Effect of HOA on movement velocity

The HOA group ascended stairs with a longer stance phase ($p = 0.040$) and stride duration ($p = 0.040$) than the control group.

During stair descent, the HOA group had longer stance phase ($p = 0.047$) and stride duration ($p = 0.039$), and lower peak vertical CoM acceleration ($p = 0.046$) compared to the control group.

3.2. Effect of HOA on sagittal hip and trunk motion and anteroposterior dynamic balance

During stair ascent, neither peak hip flexion angle ($p = 0.614$) nor sagittal trunk motion differed between groups (backward lean: $p = 0.690$; forward lean: $p = 0.746$). However, there was greater maximal anterior MoS in the HOA group ($p = 0.018$) than in the control group. SPM analysis showed a supra-threshold cluster for anterior MoS during stair ascent from 0 to 96 % single-support phase with higher values for the HOA group ($p = 0.025$; **Fig. S5**).

During stair descent, neither peak hip flexion angle ($p = 0.424$) nor sagittal trunk motion (backward lean: $p = 0.189$; forward lean: $p = 0.276$) differed between groups. Likewise, no difference in anteroposterior dynamic balance between HOA and control group was found (min. MoS anterior: $p = 0.052$; min. MoS posterior: $p = 0.202$; max. MoS anterior: $p = 0.073$; max. MoS posterior: $p = 0.165$).

Table 2
Participant demographic and clinical characteristics.

Characteristics	HOA group	Control group
Male/Female	11/10	11/10
Age (years)	64.0 (9.6)	63.1 (9.2)
Height (cm)	171.2 (6.6)	171.1 (8.6)
Body mass (kg)	71.3 (11.6)	74.4 (12.4)
BMI (kg/m^2)	24.2 (2.9)	25.2 (2.7)
HOOS	62.0 (16.4)	97.7 (5.1)
Functional leg length (cm)	79.0 (4.0)	79.5 (6.2)
Affected limb (left/right)	10/11	

Mean (SD). HOA = hip osteoarthritis; BMI = Body Mass Index; HOOS = Hip Osteoarthritis Outcome Score. Functional leg length = crotch height during upright standing (Choi & Ashdown, 2011).

3.3. Effect of HOA on frontal hip and trunk motion and mediolateral dynamic balance

During stair ascent, peak hip adduction ($p = 0.071$) and abduction ($p = 0.342$) angles did not differ between groups. However, lower frontal hip RoM was found in the HOA group compared to the control group ($p = 0.019$). Peak hip external rotation angle ($p = 0.349$), ipsilateral trunk lean ($p = 0.862$) and mediolateral MoS parameters (min. MoS medial: $p = 0.893$; min. MoS lateral: $p = 0.880$; max. MoS medial: $p = 0.806$; max. MoS lateral: $p = 0.675$) did not differ between groups.

During stair descent, peak hip adduction ($p = 0.196$) and abduction ($p = 0.421$) angles did not differ between groups. Likewise, peak hip external rotation angle ($p = 0.504$), ipsilateral trunk lean ($p = 0.615$) and mediolateral MoS parameters (min. MoS medial: $p = 0.606$; min. MoS lateral: $p = 0.211$; max. MoS medial: $p = 0.163$; max. MoS lateral: $p = 0.271$) did not differ between groups.

3.4. Effect of HOA on external hip joint moments

During stair ascent, the HOA group had a lower peak internal rotation moment compared to the control group ($p = 0.021$).

During stair descent, no differences in hip joint moments were found between the HOA and the control group.

4. Discussion

This was the first study to analyse biomechanics and task-specific dynamic balance during steady-state stair walking in participants with mild-to-moderate HOA. We found that during stair ascent, the HOA group had longer stride and stance phase duration, greater anterior margin of stability, but lower frontal hip RoM and hip external rotation moment compared to the control group. For stair descent, longer stance phase and stride duration, and lower peak vertical CoM acceleration were found in the HOA group compared to the control group.

4.1. People with HOA ascent and descent stairs with lower movement velocity

As hypothesized, movement velocity was lower in the HOA group than in the control group for both movement tasks, with longer stance and stride durations. This finding is in line with results from Hall et al. (2017), who also found longer stance duration during stair ascent and descent on a one-step staircase, and thus seems to be a consistent gait feature in people with HOA during gait-to-stair transition and steady-state stair walking. However, no reductions in anteroposterior and vertical CoM velocity were found between groups. While this aligns with the results from Popovic et al. (2021), it contradicts those of Hall et al. (2017). However, Hall et al. (2017) included subjects with more severe HOA and calculated movement velocity by dividing stride length by stride time as opposed to the CoM velocity used in our study. Popovic et al. (2021) did not report the method for velocity calculation, but values reported in their study were twice as high as in the present study or the study of Hall et al. (2017) and, thus, are likely not comparable.

Additionally, we found lower peak vertical CoM acceleration during stair descent. This parameter has also been found to be lower in healthy older people than younger people (Buckley et al., 2013), caused by greater muscular co-contraction resulting in a stiffening of the limb. While greater muscular co-contraction reduces gait efficiency (Peterson & Martin, 2010), it might help to avoid high joint and muscle forces in the contralateral limb, which has to decelerate the CoM after IC. Analyses of muscle activity and joint contact forces during steady-state stair walking are needed to verify this hypothesis in people with HOA. If found valid, strengthening weakened hip and knee extensors might allow people with HOA to adopt a faster and more efficient movement pattern, especially during stair descent.

Table 3
Biomechanical parameters during stair ascent.

		Parameter during stair ascent	HOA group mean (SD)	Control group mean (SD)	Mean difference (95 % CI)	*t*-test/MWU *p* (|d|)
Sagittal plane	Hip	Minimum angle/peak extension [°]	−9.94 (4.87)	−9.78 (4.80)	0.16 (−2.86 3.18)	0.915 (0.03)
		Maximum angle/peak flexion [°]	47.76 (7.67)	48.92 (7.02)	1.15 (−3.43 5.74)	0.614 (0.16)
		Range of motion [°]	57.70 (5.73)	58.69 (5.36)	0.99 (−2.47 4.45)	0.565 (0.18)
		Peak ext. extension moment [Nm/kg]	0.54 (0.37)	0.38 (0.40)	−0.16 (−0.40 0.09)	0.087 (0.40)
		Peak ext. flexion moment [Nm/kg]	−1.14 (0.40)	−1.32 (0.41)	−0.18 (−0.43 0.08)	0.167 (0.43)
	Trunk	Minimum angle/peak backward lean [°]	−3.34 (13.97)	−1.72 (16.46)	1.62 (−7.90 11.14)	0.690 (0.11)
		Maximum angle/peak forward lean [°]	0.53 (14.19)	2.08 (16.36)	1.55 (−8.00 11.10)	0.746 (0.10)
	MoS	Minimum anterior [cm]	−15.60 (4.00)	−17.80 (3.00)	−2.20 (−4.37 0.04)	0.054 (0.61)
		Minimum posterior [cm]	14.90 (2.80)	16.10 (2.60)	1.20 (−0.47 2.94)	0.330 (0.45)
		Maximum anterior [cm]	4.00 (3.20)	1.60 (2.90)	**−2.40 (−4.26 – 0.43)**	**0.018 (0.76)**
		Maximum posterior [cm]	34.40 (3.50)	35.50 (2.60)	1.10 (−0.81 3.02)	0.250 (0.36)
Frontal plane	Hip	Minimum angle/peak adduction [°]	−8.92 (3.96)	−10.96 (3.14)	−2.04 (−4.27 0.18)	0.071 (0.57)
		Maximum angle/peak abduction [°]	3.54 (2.85)	4.33 (2.50)	0.80 (−0.88 2.47)	0.342 (0.30)
		Range of motion [°]	12.45 (3.45)	15.29 (4.08)	**2.84 (0.48 5.20)**	**0.019 (0.75)**
		Peak ext. adduction moment [Nm/kg]	−0.47 (0.22)	−0.50 (0.26)	−0.03 (−0.18 0.12)	0.670 (0.13)
		Peak ext. abduction moment [Nm/kg]	0.20 (0.14)	0.28 (0.19)	0.08 (−0.02 0.19)	0.160 (0.50)
	Trunk	Minimum angle/peak contralateral lean [°]	−2.45 (1.23)	−2.23 (2.25)	0.22 (−0.91 1.35)	0.901 (0.12)
		Maximum angle/peak ipsilateral lean [°]	2.40 (2.34	2.25 (2.09)	−0.16 (−1.54 1.23)	0.862 (0.07)
	MoS	Minimum medial [cm]	−3.10 (2.10)	−3.10 (1.40)	0.00 (−1.05 1.20)	0.893 (0.04)
		Minimum lateral [cm]	8.30 (1.00)	8.30 (0.80)	0.00 (−0.54 0.63)	0.880 (0.05)
		Maximum medial [cm]	1.90 (1.20)	1.80 (0.80)	−0.10 (−0.71 0.56)	0.806 (0.08)
		Maximum lateral [cm]	13.20 (2.00)	13.00 (1.30)	−0.20 (−1.28 0.84)	0.675 (0.13)
Transverse plane	Hip	Minimum angle/peak int. rotation [°]	−4.55 (10.79)	−7.89 (12.50)	−3.34 (−10.62 3.94)	0.360 (0.29)
		Maximum angle/peak ext. rotation [°]	5.79 (11.14)	2.42 (11.94)	−3.38 (−10.58 3.83)	0.349 (0.29)
		Range of motion [°]	10.35 (1.84)	10.31 (3.05)	−0.04 (−1.61 1.53)	0.636 (0.01)
		Peak ext. internal rotation moment [Nm/kg]	−0.13 (0.08)	−0.19 (0.09)	**−0.06 (−0.11 −0.01)**	**0.021 (0.69)**
		Peak ext. external rotation moment [Nm/kg]	0.17 (0.06)	0.15 (0.05)	−0.02 (−0.05 0.02)	0.335 (0.30)
Spatiotemporal		Stance phase duration [s]	0.80 (0.14)	0.72 (0.07)	**−0.07 (−0.14 0.00)**	**0.040 (0.66)**
		Stride duration [s]	1.24 (0.19)	1.14 (0.11)	**−0.10 (−0.20 –0.01)**	**0.040 (0.66)**
		Mean anteroposterior CoM velocity [m/s]	0.47 (0.07)	0.50 (0.05)	0.03 (−0.01 0.07)	0.092 (0.53)
		Mean vertical CoM velocity [m/s]	0.30 (0.04)	0.31 (0.03)	0.02 (−0.01 0.04)	0.157 (0.45)
		Peak anteroposterior CoM acceleration [cm/s^2]	0.50 (0.20)	0.40 (0.10)	−0.10 (−0.13 0.06)	1.000 (0.21)
		Peak vertical CoM acceleration [cm/s^2]	2.50 (0.70)	2.30 (0.50)	−0.20 (−0.59 0.17)	0.271 (0.34)

SD = standard deviation; 95 % CI = 95 % confidence intervals; MoS = margin of stability; HOA = hip osteoarthritis; CoM = centre of mass. P-values as found by independent sample t-tests/Mann-Whitney-U tests (MWU); significant results ($p < 0.05$) in bold.

4.2. People with HOA ascent stairs with greater anteroposterior margin of stability

We expected to find differences in sagittal plane hip and trunk kinematics. In line with the results from Popovic et al. (2021) but contrary to Hall et al. (2017), we did not see an effect of HOA on sagittal hip RoM or peak hip flexion during stair ascent or descent. Hall et al. (2017) reported lower peak flexion and RoM during stair ascent. Overall, a greater sagittal hip RoM was described in their study, likely due to the larger riser height (20–24 cm vs. 17 cm in the present study), causing a greater hip flexion angle at IC. Yet, this contradicted previous literature's findings that reported larger hip flexion angles during steady-state stair walking compared to gait-to-stair transition (Alcock et al., 2014; Andriacchi et al., 1980). Lastly, subjects in the study by Hall et al. (2017) had more severe HOA, which likely affected hip sagittal mobility (Baker et al., 2016).

Despite a lack of sagittal kinematic changes in our study, alterations in anterior stability were found. The HOA group had a greater peak anterior MoS and greater anterior MoS across nearly the entire stance phase of stair ascent in the SPM analysis compared to the control group. Therefore, participants with HOA seem to have adopted a more stable movement strategy during stair ascent. During steady-state stair walking, foot placement can only impact the anterior edge of the BoS to a small extent due to the dimensions of the tread, and in our study, no reduction in anteroposterior CoM velocity was found. Therefore, the greater MoS could either stem from a reduction in pendulum length, e.g., by greater knee flexion, or a combination of smaller modifications in CoM velocity, foot placement or pendulum length that did not reach statistical significance but still impacted the MoS. Yet, despite the greater MoS observed in the HOA group, both groups showed a negative anterior MoS throughout large parts of the single-support phase, which is necessary for an energetically efficient transition to the next step (Kuo et al., 2005). Therefore, the lower negative anterior MoS observed in the HOA group compared to the control group might have resulted from a

Table 4
Biomechanical parameters during stair descent.

		Parameter during stair descent	HOA group	Control group	Mean difference	*t*-test/MWU
			mean (SD)	mean (SD)	(95 % CI)	*p* (|d|)
Sagittal plane	Hip	Minimum angle/peak extension [°]	−6.67 (6.12)	−5.87 (4.85)	0.81 (−2.64 4.25)	0.638 (0.15)
		Maximum angle/peak flexion [°]	23.01 (9.85)	25.20 (7.60)	2.19 (−3.29 7.68)	0.424 (0.25)
		Range of motion [°]	29.68 (5.84)	31.06 (4.17)	1.38 (−1.78 4.55)	0.382 (0.27)
		Peak ext. extension moment [Nm/kg]	1.51 (0.34)	1.45 (0.21)	−0.06 (−0.23 0.12)	0.516 (0.20)
		Peak ext. flexion moment [Nm/kg]	−0.14 (0.18)	−0.12 (0.13)	0.03 (−0.07 0.12)	0.960 (0.16)
	Trunk	Minimum angle/peak backward lean [°]	0.47 (3.77)	2.27 (4.87)	1.80 (−0.92 4.51)	0.189 (0.41)
		Maximum angle/peak forward lean [°]	5.24 (3.79)	6.81 (5.31)	1.57 (−1.30 4.45)	0.276 (0.34)
	MoS	Minimum anterior [cm]	−20.00 (2.70)	−21.70 (3.00)	−1.70 (−3.54 0.02)	0.052 (0.62)
		Minimum posterior [cm]	24.30 (4.10)	26.10 (3.80)	1.80 (−0.65 4.33)	0.202 (0.46)
		Maximum anterior [cm]	−1.30 (3.60)	−3.20 (2.80)	−1.90 (−3.87 0.18)	0.073 (0.57)
		Maximum posterior [cm]	42.20 (3.00)	43.70 (3.70)	1.50 (−0.63 3.59)	0.165 (0.44)
Frontal plane	Hip	Minimum angle/peak adduction [°]	−6.80 (2.82)	−8.10 (3.58)	−1.31 (−3.31 0.70)	0.196 (0.41)
		Maximum angle/peak abduction [°]	4.42 (2.76)	5.08 (2.44)	0.65 (−0.97 2.28)	0.421 (0.25)
		Range of motion [°]	11.22 (4.03)	13.18 (3.52)	1.96 (−0.40 4.32)	0.132 (0.52)
		Peak ext. adduction moment [Nm/kg]	−0.34 (0.23)	−0.42 (0.27)	−0.08 (−0.23 0.08)	0.230 (0.32)
		Peak ext. abduction moment [Nm/kg]	0.57 (0.28)	0.60 (0.34)	0.03 (−0.16 0.22)	0.747 (0.10)
	Trunk	Minimum angle/peak contralateral lean [°]	−1.61 (1.29)	−1.27 (2.24)	0.34 (−0.79 1.48)	0.550 (0.19)
		Maximum angle/peak ipsilateral lean [°]	1.58 (1.60)	1.28 (2.24)	−0.30 (−1.52 0.91)	0.615 (0.16)
	MoS	Minimum medial [cm]	−5.60 (2.20)	−6.00 (2.40)	−0.40 (−1.80 1.06)	0.606 (0.16)
		Minimum lateral [cm]	9.20 (1.60)	9.70 (1.70)	0.50 (−0.53 1.55)	0.211 (0.31)
		Maximum medial [cm]	0.30 (1.00)	−0.10 (1.20)	−0.40 (−1.15 0.20)	0.163 (0.44)
		Maximum lateral [cm]	14.80 (2.10)	15.20 (2.90)	0.40 (−1.16 1.98)	0.271 (0.16)
Transverse plane	Hip	Minimum angle/peak int. rotation [°]	−3.96 (9.90)	−7.54 (14.02)	−3.58 (−11.15 3.98)	0.344 (0.30)
		Maximum angle/peak ext. rotation [°]	9.20 (11.10)	6.60 (13.70)	−2.60 (−10.37 5.18)	0.504 (0.21)
		Range of motion [°]	13.15 (4.58)	14.14 (4.76)	0.99 (−1.92 3.90)	0.496 (0.21)
		Peak ext. internal rotation moment [Nm/kg]	−0.19 (0.11)	−0.22 (0.11)	−0.03 (−0.10 0.04)	0.330 (0.27)
		Peak ext. external rotation moment [Nm/kg]	0.22 (0.11)	0.26 (0.10)	0.04 (−0.03 0.10)	0.256 (0.36)
Spatiotemporal		Stance phase duration [s]	0.70 (0.12)	0.63 (0.07)	**−0.06 (−0.13 0.00)**	**0.047 (0.63)**
		Stride duration [s]	1.09 (0.19)	0.99 (0.11)	**−0.10 (−0.20 −0.01)**	**0.039 (0.66)**
		Mean anteroposterior CoM velocity [m/s]	0.53 (0.09)	0.57 (0.07)	0.04 (−0.01 0.09)	0.079 (0.56)
		Mean vertical CoM velocity [m/s]	0.32 (0.06)	0.35 (0.04)	0.03 (0.00 0.06)	0.068 (0.58)
		Peak anteroposterior CoM acceleration [cm/s^2]	0.70 (0.20)	0.70 (0.20)	0.00 (−0.08 0.12)	0.306 (0.11)
		Peak vertical CoM acceleration [cm/s^2]	1.40 (0.30)	1.60 (0.30)	**0.20 (0.00 0.40)**	**0.046 (0.63)**

SD = standard deviation; 95 % CI = 95 % confidence intervals; MoS = margin of stability; HOA = hip osteoarthritis; CoM = centre of mass. P-values as found by independent sample t-tests/Mann-Whitney-U tests (MWU); significant results ($p < 0.05$) in bold.

movement strategy that reduced the risk of falling at the cost of reduced gait efficiency (Bosse et al., 2012).

4.3. Lower frontal hip mobility in people with HOA does not impact mediolateral dynamic balance

We expected the HOA group to show more pronounced hip abduction, hip external rotation and ipsilateral trunk lean to increase mediolateral postural stability during stair ascent and descent compared to the control group. In contrast to our hypothesis and previous literature findings (Hall et al., 2017; Popovic et al., 2021), no group differences in frontal plane peak angles during both movement tasks were found in the current study. However, the HOA group showed lower frontal hip RoM of about 20 % during stair ascent compared to the control group, similar to previous studies during gait-to-stair transition or level walking (Hall et al., 2017; Rutherford et al., 2015). This reduction likely originated in lower hip adduction rather than abduction. As HOA causes decreased hip abduction strength (Loureiro et al., 2018) and gluteus medius activity (Zacharias et al., 2020), reducing hip adduction is a strategy for lowering required hip abduction forces in people with HOA (Meyer et al., 2018). However, the lower frontal hip RoM did not translate into changes in mediolateral stability. Yılmaz and Bağcıer (2022) found an effect of HOA severity on mediolateral but not anteroposterior stability with more severe HOA causing worse stability scores during a stationary balance task. Therefore, mediolateral stability might only be impaired in people with more severe HOA and, consequently, larger impairments of hip abductor strength than observed in the participants of the present study. As the gluteus medius does not only serve as the main stabilizer of mediolateral CoM movement during stair ascent and descent, but also contributes substantially to the forward acceleration of the CoM during stair descent (Lin et al., 2015), HOA severity might also impact the anteroposterior CoM velocity, as discussed in chapter 4.1. Future studies

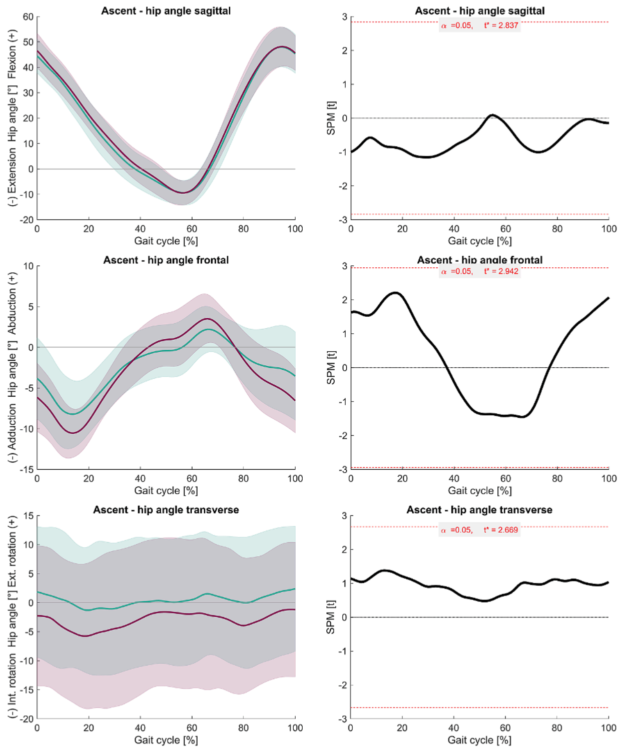

Fig. 2. Hip angle time curves (mean ± SD) during stair ascent with results from SPM analysis. Green line = HOA group, purple line = control group.

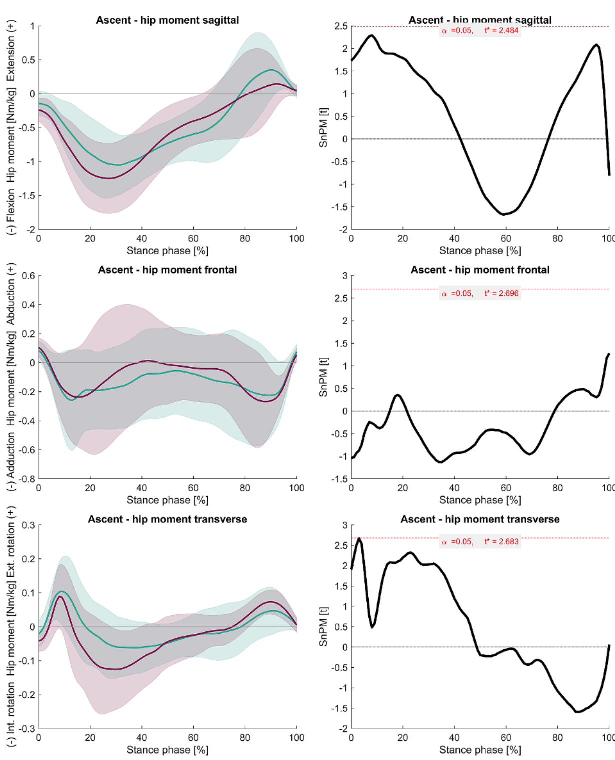

Fig. 3. Hip moment time curves (mean ± SD) during stair ascent with results from SnPM analysis. Green line = HOA group, purple line = control group.

must clarify the role of HOA severity and hip abductor strength on the mediolateral dynamic balance and the anteroposterior CoM velocity during stair walking.

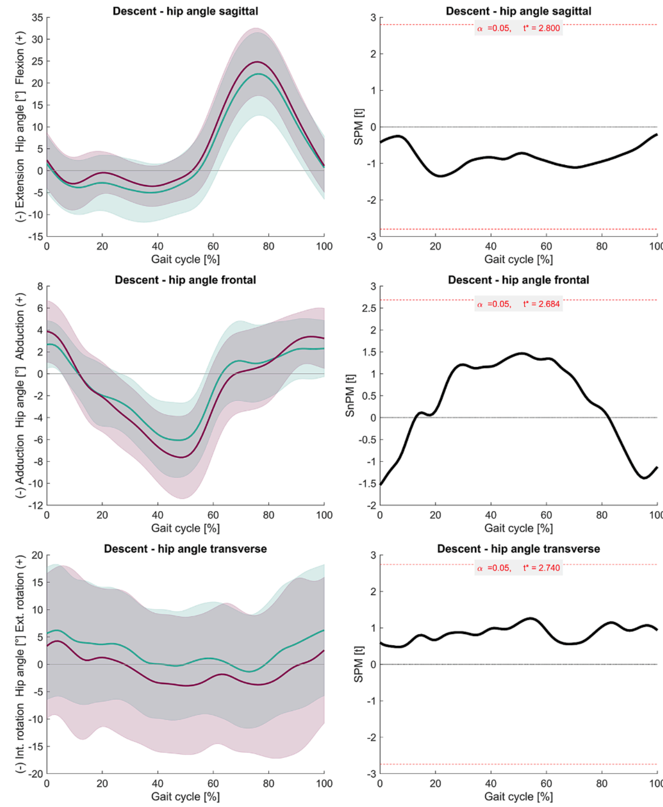

Fig. 4. Hip angle time curves (mean ± SD) during stair descent with results from SPM and SnPM analyses. Green line = HOA group, purple line = control group.

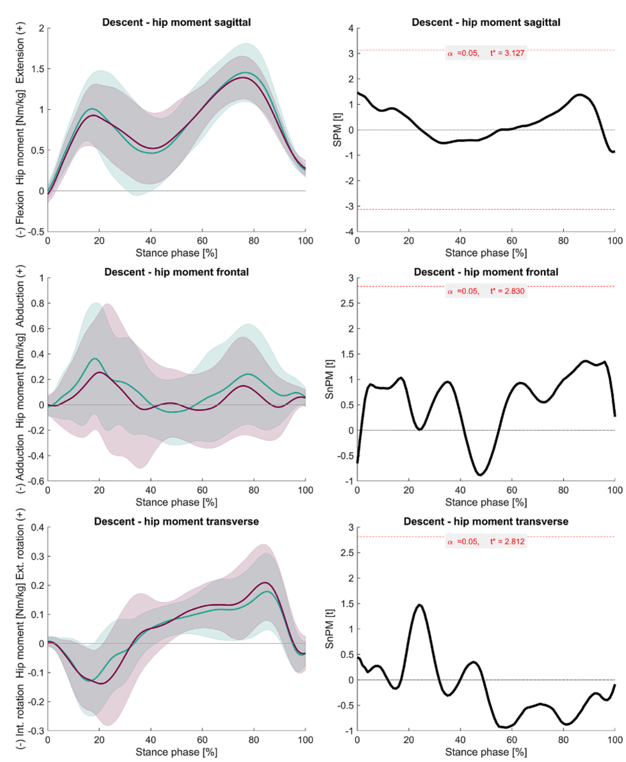

Fig. 5. Hip moment time curves (mean ± SD) during stair descent with results from SPM and SnPM analyses. Green line = HOA group, purple line = control group.

4.4. People with HOA ascent stairs with lower hip internal rotation moments

We hypothesized that participants with HOA would show lower external hip joint moments in all movement planes. However, only lower peak hip internal rotation moments of about 32 % were found during stair ascent in the HOA group compared to the control group. This finding contradicts previous literature that found lower hip external rotation moments during stair ascent in HOA participants compared to control participants (Hall et al., 2017) or found the reduction in hip external rotation moments to be the parameter with the highest explained variance during stair ascent in an HOA group (Meyer et al., 2016). However, both studies included subjects with more severe HOA than the present study. Peak internal rotation moments during stair ascent occur at around 30 % of the stance phase, where hip flexion is high. As the gluteus medius muscle also serves as a hip internal rotator, especially in hip flexion (Delp et al., 1999), lower abductor muscle force likely impacts transverse plane hip kinematics and dynamics. Yet, further investigation is warranted as force capacity and muscular activity were not captured during our study. For level walking, it has been shown that reductions in hip moments depend on HOA severity (Diamond et al., 2018). The results of our study imply that this could also be the case for stair walking.

4.5. Strengths and limitations

This was the first study to use a multi-step instrumented staircase to comprehensively assess steady-state stair walking biomechanics and dynamic balance in participants with mild-to-moderate HOA compared to a well-matched healthy control group. Thereby, not only discrete time points but also analyses of time series were conducted using SPM. Alongside these strengths of our study, some limitations have to be considered.

Angle and moment time curves often showed large standard deviations and thus, small group effects might have been hidden by large interindividual heterogeneity. While the sample size of the present study was comparable to or larger than in studies on people with more severe HOA (Hall et al., 2017; Meyer et al., 2016), it was smaller than in another study on people with mild-to-moderate HOA symptoms (Popovic et al., 2021). Therefore, larger sample sizes might be necessary to detect differences between groups in people with mild-to-moderate symptoms where the disease impact on joint biomechanics is less pronounced than in people with more severe forms of HOA.

Participants in our study ascended and descended stairs at a self-selected speed, and our results showed lower movement velocity of the HOA group in terms of longer stance and stride duration but not in terms of altered CoM velocity. As the gait velocity correlates with hip joint kinematics and dynamics (Lelas et al., 2003; Fukuchi et al., 2019), differences in movement speed might have impacted our results. However, self-selected movement velocity allows participants to keep their natural movement pattern and was also chosen in other studies (Hall et al., 2017; Popovic et al., 2021). We refrained from using an ANCOVA with movement velocity as a covariate as differences in movement velocity are not a source of random error variability but rather representative of the population characteristics (Astephen Wilson, 2012).

For the estimation of task-specific dynamic balance, an anatomical definition of the BoS based on markers was applied in the current study. Yet, this definition of the BoS can over- or underestimate the MoS (Curtze et al., 2024), as only about one-third of the physiological BoS can effectively be used for balance control during standing (Hof & Curtze, 2016). However, as the definition of the BoS was equal for both groups, this issue should not have influenced our findings or their interpretation.

Additionally, the interpretation of joint loading based on external joint moments is limited as muscle forces or forces of elastic structures are disregarded. Therefore, future studies should expand these findings using analysis of muscle activation and musculoskeletal modelling methods (Weinhandl & Bennett, 2019). Higher levels of muscular co-contraction have been reported in people with HOA (Diamond et al., 2020). They could also cause the reduced vertical CoM acceleration observed in our study, thus affecting joint loading.

5. Conclusion

We examined hip and trunk biomechanics and dynamic balance during steady-state stair walking in people with mild-to-moderate HOA. Despite the demanding nature of this task, no differences in trunk motion, and only a few alterations in hip biomechanics with lower frontal hip RoM and peak internal rotation moment during stair ascent were found in the HOA group compared to the control group. Yet, a greater anterior margin of stability showed that people with HOA modified their gait pattern during stair ascent to be more stable but potentially less efficient. Lastly, lower peak vertical CoM acceleration during stair descent was observed in the HOA group, which could have been caused by a stiffening strategy to reduce joint loading. Therefore, future studies must clarify the role of muscle strength and muscular co-contraction on steady-state stair walking biomechanics and gait efficiency in people with mild-to-moderate HOA.

CRediT authorship contribution statement

Hannah Steingrebe: Writing – original draft, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Stefan Sell:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Hannah Ehmann:** Writing – review & editing, Visualization, Investigation. **Thorsten Stein:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

Stefan Sell reports a relationship with Bauerfeind AG that includes medical advisory. Hannah Steingrebe, Hannah Ehmann and Thorsten Stein declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.112709.

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