

Medial Longitudinal Arch Deformation during Walking and Stair Navigation while Carrying Loads

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ABSTRACT

Background: Understanding the biomechanics of the medial longitudinal arch (MLA) may provide insights into injury risk and prevention, as well as function of the arch-supporting structures. Our understanding of MLA deformation is currently limited to sit-to-stand, walking, and running. **Material and Methods:** Three-dimensional deformation of the MLA of the right foot was characterized in seventeen healthy participants during several simulated activities of daily living. MLA deformation was quantified by both changes in arch length and navicular displacement during the stance phase of three motions: walking, stair ascent, and stair descent. Three levels of load were also considered: no load, a front load (13.6 kg), and a backpack load (13.6 kg). Force platforms and an eight-camera motion capture system were used to collect relevant lower extremity kinetic and kinematic data. **Results:** Motion type had a significant ($p < 0.05$) effect on navicular displacement and arch length elongation with navicular displacement being greatest during stair descent, while the walking and stair descent conditions showed the greatest increase in arch length. External load did not significantly affect either of these two measures ($p > 0.05$). **Conclusion:** Differences in the MLA deformation variables resulting from varied dynamic activities of daily living can be greater than those during walking and should be considered. **Clinical Relevance:** Detailing the mechanics of the MLA may aid in further understanding injuries associated with the MLA, and the results of the current study indicate that these mechanics change based on activity.

Keywords: Medial Longitudinal Arch; Stair Ambulation; Load Carrying;

INTRODUCTION

1
2 The medial longitudinal arch (MLA) is a dynamic structure in the foot that deforms in
3 response to loading. Clinically, MLA deformation has been quantified several ways,
4 including navicular drop, a measure that Brody⁵ described as the vertical change in height of
5 the navicular tuberosity as a person moves from a seated, subtalar neutral position to a
6 standing position. During sit-to-stand, reported navicular drop values range from 5 to 11
7 mm^{2,5,10,13,29} as the load experienced by each foot increases from about 10% body weight
8 while seated⁹ to 50% body weight while standing. When moving from sitting to single-leg
9 stance, navicular drop was 4.5 mm greater than dual-leg sit-to-stand navicular drop,⁴
10 indicating that MLA deformation increases with increasing load. Additional lowering of the
11 arch with greater load is also supported by a cadaveric study.¹⁵ One limitation of the
12 navicular drop test is that it only measures vertical changes in height, while many researchers
13 have reported mediolateral motion of the navicular during gait of the same or greater
14 magnitude.^{4,7,31}

15 In addition to the previously cited studies that documented MLA changes during sit-
16 to-stand, a number of studies have explored MLA kinematics during walking. Walking
17 navicular drop varied greatly between individuals in one study, ranging from 1.7 mm to 13.4
18 mm²⁶ compared to seated navicular height. Using three-dimensional analysis to account for
19 mediolateral navicular movement during walking, navicular movement was 7.9 ± 2.5 mm
20 compared to standing navicular height.⁷

21 As navicular height decreases, arch length typically increases.^{6,12} Arch length,
22 defined as the distance between the first metatarsal head and posterior calcaneus, increased
23 by approximately 2% during walking as compared to seated arch length.⁶ Gefen¹² used
24 fluoroscopy to evaluate changes in plantar fascia length of two female participants during

25 walking and found the plantar fascia elongated by 9 to 12% compared to its length at early
26 stance phase (before forefoot contact).

27 Another relevant characteristic of arch kinematics is the timing of when peak
28 deformations occur. Peak changes in arch height/navicular movement during walking occur
29 at 50% to 85%^{6,7,16} of stance phase while maximum arch lengthening appears to peak earlier
30 at about 20% of stance and remains relatively constant until 80% of stance.⁶ The occurrence
31 of the two ground reaction force peaks at about 20% and 78% of stance phase during
32 walking¹⁶ seem to correspond to peaks in MLA deformation. For example, Kayano¹⁷
33 observed the MLA elongating due to increases in vertical ground reaction force until foot flat,
34 after which it shortened but then slightly lengthened again when the triceps surae muscles
35 were activated. Simulated walking in cadaver feet has shown plantar fascia tension increased
36 until late stance and was well correlated to Achilles tendon force ($r = 0.76$).⁸ Protopapadaki
37 et al.²⁸ noted that maximum external ankle moments occurred early in stance (~10%) during
38 stair descent and later in stance (~55%) during stair ascent, which closely mimicked the
39 maximum ground reaction force peaks. Therefore, it is feasible to believe much of the MLA
40 collapse is accounted for by muscle activity and ground reaction forces, although this has not
41 been previously quantified.

42 There are several plausible biomechanical links between MLA deformation and
43 foot/lower extremity pathologies. First, as the MLA deforms the tension in the plantar fascia
44 increases and excessive tension may lead to plantar fasciitis^{21,23} and hallux rigidus/hallux
45 limitus.¹¹ Second, change in navicular height was highly correlated ($r = 0.8$) with calcaneal
46 inversion and eversion,²² and eversion was highly coupled with internal tibial rotation,²⁷ thus
47 making the foot susceptible to injuries associated with abnormal tibial rotation or pronation.
48 This coupling of the foot and leg via the ankle-joint complex may partially explain why
49 greater navicular drop was found in medial tibial stress syndrome patients² and those with

50 anterior cruciate ligament ruptures compared to controls.³ While these retrospective studies
51 do not provide direct evidence of a link between MLA deformation and lower extremity
52 pathologies, the biomechanical changes resulting from MLA deformation may provide
53 insight into etiology and prevention strategies.

54 Collectively these studies provide quantitative data describing MLA kinematics
55 during level-ground walking and sit-to-stand activities. For a broader understanding of MLA
56 kinematics, exploration of different types of ambulation and the impact of load carriage
57 parameters may be important. The aim of the current study was to describe the deformation
58 of the MLA during various activities of daily living. Specifically, navicular displacement and
59 arch elongation were observed during standing, walking, stair ascent and descent while
60 carrying no load, a front load and a backpack load. It was hypothesized that navicular
61 displacement and arch length would increase with an external load. It was also hypothesized
62 that navicular displacement and arch length would increase with stair ambulation as
63 compared to both static standing and walking.

64 **METHODS**

65 **Participants**

66 Young healthy adults (9 males, 8 females; age (mean \pm SD): 26 ± 3 years; height:
67 1.72 ± 0.09 m; mass: 68.5 ± 9.7 kg; foot length: 250 ± 20 mm; foot breadth: 97 ± 8 mm;
68 malleolus height: 71 ± 7 mm; malleolus width: 72 ± 5 mm) from the university population
69 were recruited for this study. Potential participants were excluded if they had a history of
70 musculoskeletal or neurological condition that would preclude safe walking and stair
71 ambulation while carrying a moderate load, had current lower extremity discomfort, or wore
72 foot orthotics. Experimental procedures were approved by the Iowa State University
73 Institutional Review Board and all participants provided written informed consent prior to
74 participation.

75 **Apparatus**

76 The experimental walkway for the walking trials was 5 m in length and the
77 experimental staircase consisted of two steps (step height 18.5 cm, tread length 29.5 cm) and
78 a top landing. During the front load trials, participants held a two-handled crate (20x31x20
79 cm, 13.6 kg total load). This mode of front load was chosen as it is more commonly
80 encountered in the workforce than a front pack, and the selected mass is within the range
81 (12.5 to 20 kg) previously used in other weighted-carry studies.^{1,19} During the backpack load
82 trials, participants wore a custom fitted, internal frame backpack (Kelty, Boulder, CO, USA)
83 with a total mass of 13.6 kg.

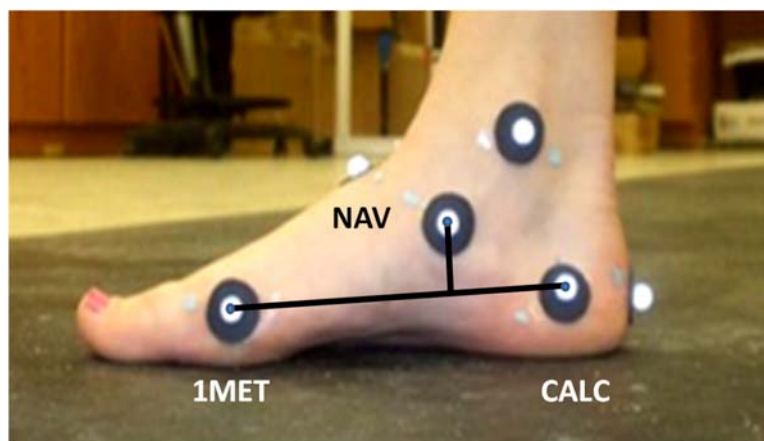
84 Kinematic and kinetic recordings were collected simultaneously from an eight-
85 camera, three-dimensional motion analysis system (Vicon, Oxford, UK), with a resolution of
86 at least 1 ± 1 mm. Ten millimeter diameter retro-reflective markers were placed on the
87 malleoli, navicular tuberosity, dorsifoot, first metatarsal head (2 cm from supporting surface),
88 and medial calcaneus (2 cm from the supporting surface) of the right foot according to
89 Nielsen et al.²⁶ while participants stood in equal-weight bearing on a custom-built apparatus
90 for foot measurements. The medial calcaneus marker was placed 3 cm and 4 cm anterior
91 from the most posterior aspect of the foot for females and males, respectively.² A posterior
92 heel marker was placed in the center of the Achilles tendon, 2 cm from the supporting
93 surface. The first metatarsal, navicular and calcaneus represent separate segments of the foot
94 that experience significant sagittal plane rotation proposed by other researchers.^{25,35}

95 Compared to radiographs, validity intraclass correlation coefficients range from 0.712
96 to 0.765 and 0.874 to 0.918 for truncated foot length and navicular height, respectively,
97 measured using calipers with a resolution of 1 mm, similar to the anthropometry set used in
98 the current study to mark the skin where the reflective markers would be placed.³⁴ While the
99 variables and measurement tools are slightly different than the current study, similar validity

100 may be expected. Measurement error due to skin artifact over the first metatarsal head,
101 navicular and medial calcaneus range from 1.2 to 3.3 mm.³⁰

102 Additional 1.9 cm diameter retro-reflective markers were placed on the malleoli, heel,
103 dorsifoot and lateral aspect of the left foot, acromion processes, anterior and posterior
104 superior iliac spines, greater trochanters, anterior thighs, medial and lateral femoral condyles,
105 anterior shanks and sacrum.

106 Arch length was the three-dimensional distance from the medial calcaneus marker and
107 first metatarsal head marker. Lengthening of the arch is expressed as a positive value from
108 the reference unloaded standing trial. Navicular height was the three-dimensional,
109 perpendicular distance from the navicular tuberosity marker to the line segment defined by
110 the two endpoints of arch length (Figure 1). Change in navicular height was termed navicular
111 displacement because it represents a three-dimensional movement of the navicular. It was
112 also relative to the unloaded standing trial. A smaller distance from the navicular to arch
113 length line is expressed as a positive value. Collectively, therefore, greater arch collapse is a
114 positive value. Two in-ground and two portable force platforms (AMTI, Watertown, MA,
115 USA) positioned on the first and second stair steps captured ground reaction forces.
116 Kinematic data and ground reaction forces were sampled at 160 Hz and 960 Hz, respectively.



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119 Figure 1. Arch length and navicular height (CALC: medial calcaneus, 1MET: first metatarsal
120 head; NAV: navicular tuberosity).

121 **Experimental Design**

122 There were two independent variables in this study: MOTION and LOAD. The three
123 levels of MOTION were: walking, stair ascent, and stair descent. The three levels of LOAD
124 were: no load, front load (13.6 kg) and backpack load (13.6 kg) for a total of nine conditions
125 (a 3×3 randomized complete block design with participants acting as blocks).

126 There were six dependent measures: 1) peak arch length elongation, 2) time to peak
127 arch length elongation, 3) peak navicular displacement, 4) time to peak navicular
128 displacement, 5) peak vertical ground reaction force, and 6) time to peak vertical ground
129 reaction force. Times were expressed as a percent of the stance phase.

130 **Procedure**

131 In order to accurately measure the movement of the arch, the participants remained
132 barefooted throughout the experiment. The gathered anthropometrics included height, whole
133 body mass, right foot length, breadth, malleolus height and malleolus width. Markers were
134 then placed according to the locations outlined in Apparatus above.

135 Testing began with three upright standing trials followed by a randomized
136 presentation of each condition (five trials per condition). All participants were instructed to
137 walk, ascend and descend stairs at a self-selected pace. During front load trials, participants
138 held a crate (front load) at navel height, resting it against their body if desired. To reduce
139 fatigue, participants were relieved of the front load between trials. After completing all
140 experimental trials, two upright standing trials were performed to note if there were time-
141 dependent changes in the MLA variables.

142 **Data Processing and Analysis**

143 All data were analyzed during the stance phase of walking and on the second step of
144 both stair ascent and descent (right foot in all cases). A fourth order, symmetric Butterworth
145 filter was applied to the video data with a cutoff frequency of 6 Hz, and the same filter was

146 applied to the ground reaction force data with a 20 Hz cut-off frequency. The values for the
147 five trials for an experimental condition were averaged for each participant and the means
148 and standard deviations of all participants were calculated. Time at which peak values
149 occurred was expressed as a percentage of the stance phase.

150 Statistical analysis was performed using SAS (Version 9.2, SAS, Cary, NC, USA).
151 Prior to any statistical analysis, the assumptions of the ANOVA procedures (homogeneity of
152 variances of the residuals, residuals normally distributed, and independence of observations)
153 were evaluated using the techniques advocated by Montgomery.²⁴ Once these assumptions
154 were verified, a MANOVA was performed to evaluate the effects of the independent
155 variables on the set of dependent variables collectively, thereby controlling for the
156 experiment-wise error rate. Univariate ANOVA procedures were then conducted and a
157 Tukey-Kramer post-hoc test was performed to further explore the significant effects. The
158 criteria p -value of $p < 0.05$ was used for all statistical tests.

159 RESULTS

160 The results of the MANOVA showed that both MOTION and LOAD had significant
161 effects and were considered in subsequent univariate analyses (Table 1), while the
162 MOTION×LOAD interaction was not significant ($p = 0.25$) and was not considered further.
163 Subsequent univariate ANOVA further explored these main effects and showed that
164 MOTION had a significant effect on both the magnitude of the peak navicular displacement
165 (Figure 2) and the magnitude of the peak arch length elongation (Figure 3). Arch
166 lengthening was greatest during walking and stair descent, and navicular displacement was
167 greatest during stair descent. MOTION also had a significant effect on the timing of the peak
168 navicular displacement, with peak displacement occurring at 60% of stance phase in stair
169 ascent and 75 to 76% during walking and descent (Table 2). Exploration of the effect of
170 LOAD showed that the peak vertical ground reaction force was significantly lower in the no

171 load condition than either the front load or the back load condition. Finally, LOAD also had
 172 a significant effect on the timing of the peak vertical ground reaction force with the peak for
 173 stair descent occurring much earlier than either walking or stair ascent (Figure 4).

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Table 1: MANOVA and Univariate ANOVA Results

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Independent Variables	MANOVA	Peak Navicular Displacement	Time to Peak Navicular Displacement	Peak Arch Lengthening	Time to Peak Arch Lengthening	Peak Vertical Ground Reaction Force	Time to Peak Vertical Ground Reaction Force
MOTION	<0.0001	<0.0001	<0.0001	<0.0001	0.2417	<0.0001	<0.0001
LOAD	<0.0001	0.4569	0.5742	0.3258	0.2685	<0.0001	<0.0001

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Table 2: Time to Peak Medial Longitudinal Arch Deformation for MOTION Type (Mean ± SD)

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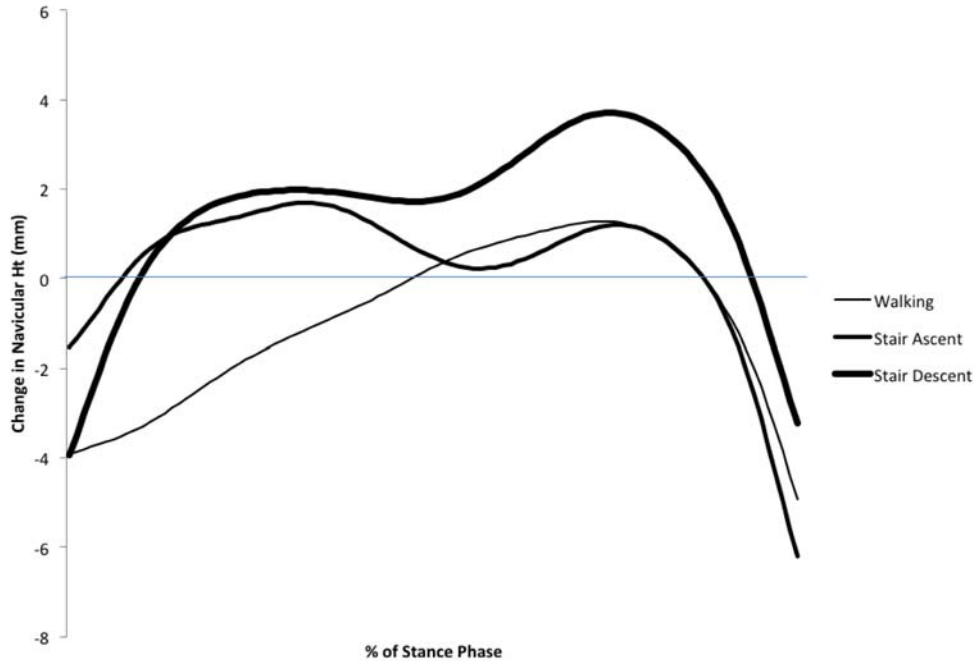
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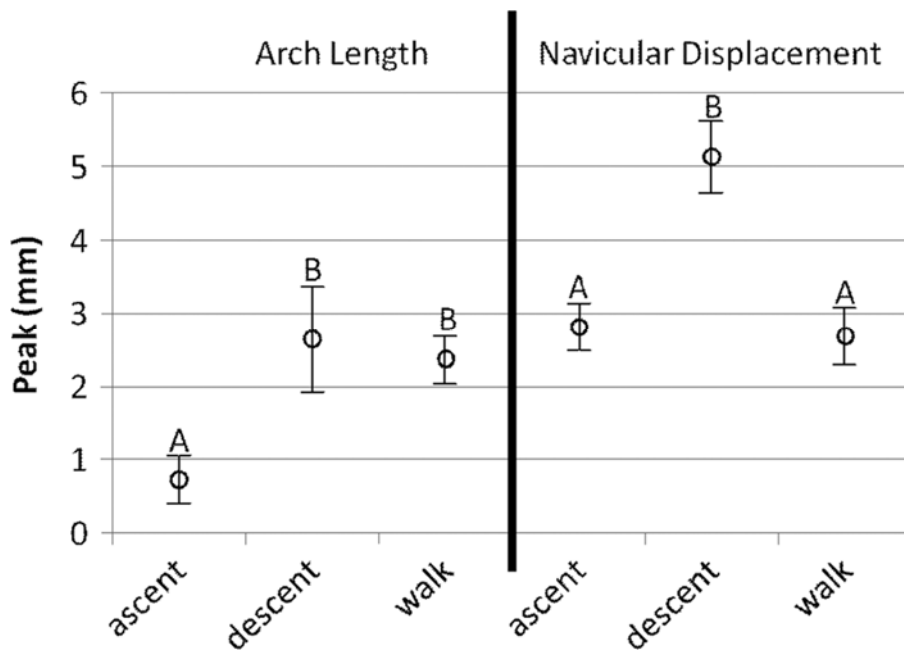
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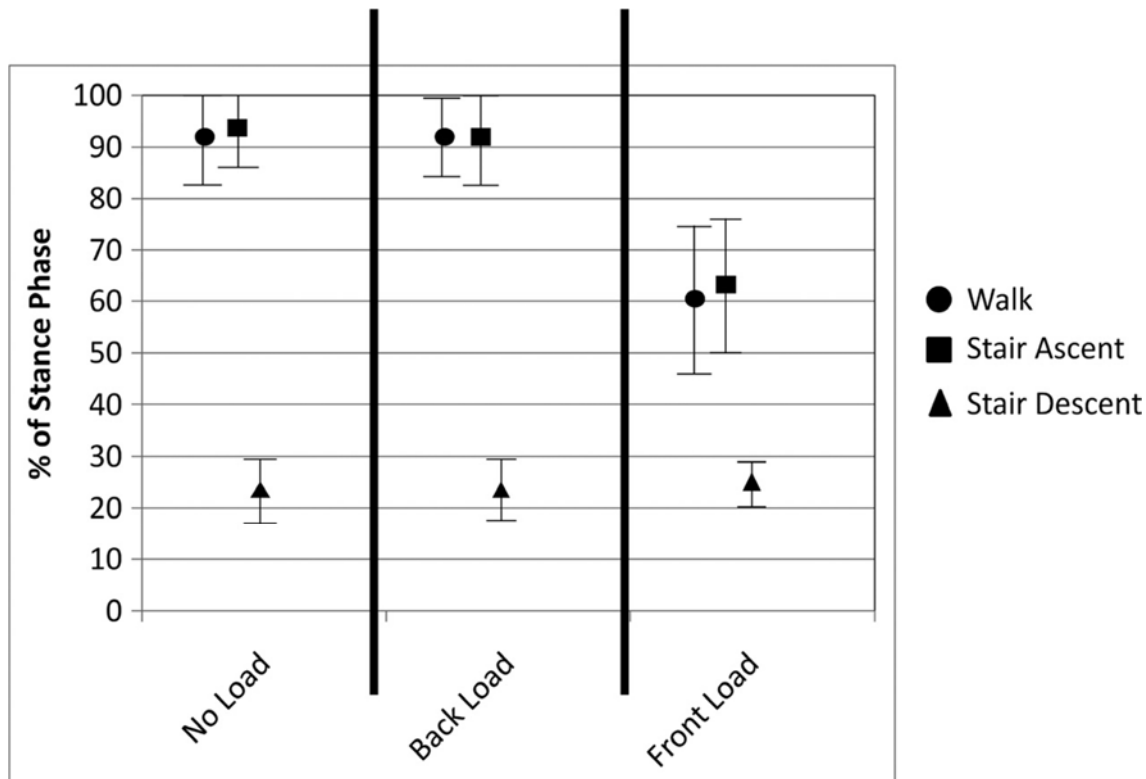
Independent Variable	Walking	Stair Ascent	Stair Descent
Time to peak navicular displacement (% stance)	76 ± 5	60 ± 20	75 ± 13
Time to peak arch length elongation (% stance)	46 ± 25	42 ± 20	50 ± 23



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 190 Figure 2. Representative navicular displacement during stance phase of walking, stair ascent,
 191 and stair descent for one trial for one participant. Zero displacement represents the
 192 same navicular height as during the static standing trial. A positive displacement
 193 represents a lower navicular height than standing and a negative



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 195 Figure 3. Mean (with 95% confidence interval) arch length elongation and navicular
 196 displacement as a function of MOTION type collapsed across load. Zero represents
 197 the same arch length and navicular height as during the static standing trial. Different
 198 letters indicate levels that are significantly different (e.g., navicular displacement
 199 during descent was greater than both ascent and walking, but ascent and walking are
 200 not statistically different from each other).



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202 Figure 4. Timing of peak vertical ground reaction force as a function of MOTION and
 203 LOAD. The 95% confidence intervals are shown.

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DISCUSSION

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The purpose of this study was to expand our understanding of the MLA deformation response by quantifying it in a new set of activities of daily living: carrying loads and navigating stairs. Deformation of the MLA is a natural motion of the foot that absorbs energy through rotation of bones and deformation of tissues, such as the plantar fascia, plantar ligaments, and muscles/tendons.¹⁸ It is important to quantify this motion in activities of daily living because excessive collapse may be related to injuries.^{2,3,11,21,23} The MLA deformations experienced during the walking trials were consistent with those previously documented.^{6,26} Navicular displacement was greatest in the stair descent task as compared to walking and ascent, and arch length elongation was significantly less in stair ascent as compared to level walking and descent. The changes in arch length observed in the current study ranged from 1.3 to 3.7%, which is similar to 2% reported by Cashmere et al.⁶ during

217 walking, but considerably less than the 9 to 12% reported by Gefen.¹² Various measurement
218 techniques, reference lengths, definitions of arch length and arch height are likely to account
219 for some of the variation in results among these studies. The magnitude of arch elongation
220 observed was well below the threshold for acute strain damage previously estimated at 9%.³³
221 While greater strain leads to greater tension, which may be related to plantar fasciitis,
222 Wearing et al.³² did not observe any differences in sagittal plane MLA motion during walking
223 between plantar fasciitis patients and controls. Therefore, it may be the repetitive loading and
224 strain rate rather than the magnitude of the strain that increases injury risk.

225 In addition to the magnitude of these deformations, also of interest was the time at
226 which these peaks occurred. The time to peak navicular displacement during walking was
227 within the range of 50 to 85% of stance reported previously.^{6,7,16} During walking and stair
228 descent, maximum navicular displacement occurred at about 76% of stance, which was
229 significantly later than stair ascent (60% of stance). This difference may be associated with
230 achieving a more rigid, supinated foot posture earlier in stance in preparation for propulsion
231 up the stairs and decreased sagittal ankle ROM during ascent compared to walking or
232 descent. Maximum change in arch length generally occurred earlier in stance compared to
233 peak navicular displacement, occurring at 42 to 50% of stance throughout all dynamic
234 conditions. There was also an interesting response for the timing of the peak ground reaction
235 force, illustrated in Figure 4. In the stair descent condition the peak vertical ground reaction
236 force always occurred early in the stance phase, reflecting the significant weight-acceptance
237 force at or near foot contact. In both walking and stair ascent conditions, the front load
238 generated an earlier timing for the peak ground reaction force indicating that the anterior
239 movement of the center of mass of the load-body system may result in a more rapid weight
240 acceptance – a result consistent with Hsiang and Chang.¹⁴

241 The effects of the external load were not quite as clear and in some cases were
242 inconsistent with our hypotheses. To begin, the effects of external load on peak ground
243 reaction forces were consistent with previous research:¹⁴ external load caused an increase in
244 peak ground reaction forces for all levels of MOTION (as compared to the no load
245 conditions). Interestingly, LOAD did not significantly affect any of the MLA deformation
246 parameters, which did not support our original hypothesis. Since a previous study did find
247 increased second metatarsal bone strain when carrying a 20 kg backpack,¹ perhaps our
248 external load was not sufficient to cause additional deformation of the MLA. However, the
249 external load (134 N) was greater than the increase in vertical ground reaction force observed
250 during unloaded walking (~80 N), both compared to standing body weight. Under the
251 dynamic conditions of the current experiment, it is difficult to separate the effects of motion
252 and the effects of load because the dynamics of stair ascent/descent generate vertical inertial
253 forces as compared to level walking. The variability in these inertial forces may have been of
254 sufficient magnitude to obfuscate the underlying effects of the 13.6 kg external load. It is
255 also possible that participants may have compensated at proximal joints to minimize arch
256 deformation from the external load, such as increased hip ROM as has been observed during
257 walking with a 12.5 kg vest.¹⁹

258 The timing of the lengthening and lowering of the arch did not always follow a
259 consistent pattern relative to the timing of the peak ground reaction force. During walking
260 and stair ascent, peak ground reaction force and navicular displacement typically occurred
261 within 5% of each other. In contrast, during stair descent the peak ground reaction force
262 occurred at approximately 23% of stance phase but maximum arch length elongation and
263 navicular displacement occurred at 50% and 76% of stance, respectively. Therefore, peak
264 navicular displacement may correspond more closely to peak plantarflexion moment, which
265 another study found to occur right before toe-off during stair ambulation.²⁰ However,

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