



Title	Forefoot and hindfoot kinematics in subjects with medial tibial stress syndrome during walking and running
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1 Forefoot and hindfoot kinematics in subjects with medial tibial stress syndrome during
2 walking and running

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19 interpreted the data and have read and approved the final submitted manuscript. Y.K.

20 had primary responsibility for the final content.

21 Abstract

22 Excessive foot pronation during static standing, walking and running has been
23 reported as a contributing factor for the development of medial tibial stress syndrome
24 (MTSS). The motion of foot pronation consists of hindfoot and forefoot motion.
25 However, no previous studies have investigated forefoot and hindfoot kinematics during
26 walking and running in subjects with MTSS. The current study sought to compare
27 hindfoot and forefoot kinematics between subjects with and without MTSS while
28 walking and running. Eleven subjects with MTSS and 11 healthy controls (each group
29 containing 10 males and one female) participated in the current study. Segment angles of
30 the hindfoot and forefoot during walking and running barefoot on a treadmill were
31 recorded using three-dimensional kinematic analysis. An independent t-test was used to
32 compare kinematic data between groups. Subjects with MTSS exhibited significantly
33 greater hindfoot eversion and abduction ($P < 0.05$) during walking and running than
34 subjects without MTSS, significantly greater forefoot eversion and abduction ($P < 0.05$)
35 during walking, and significantly greater forefoot abduction during running ($P < 0.05$).
36 Hindfoot and forefoot kinematics during walking and running were significantly
37 different between subjects with and without MTSS. For prevention and rehabilitation of
38 MTSS, it may be important to focus on not only hindfoot but also forefoot kinematics
39 during both running and walking.

40 **Keywords:** kinematics, medial tibial stress syndrome; forefoot kinematics; hindfoot
41 kinematics; walking; running

42 1. INTRODUCTION

43 Medial tibial stress syndrome (MTSS) is one of the most common overuse
44 injuries of the lower extremities.¹ The incidence of MTSS is reported to be 16%–44% in
45 a number of sports, including track and field, cross country running, and tennis.²⁻⁴ In
46 addition, a previous history of MTSS is a risk factor for further MTSS,^{1,2,5} which
47 requires a long period of rehabilitation before returning to sports participation.^{6,7} One
48 study revealed that, although patients with MTSS in whom conservative treatment failed
49 underwent surgical treatment, 59% of patients did not return to their previous
50 competition levels more than 6 months postoperatively.⁸ Therefore, it is important for
51 clinicians to understand the etiology of MTSS to improve rehabilitation programs.

52 Previously reported risk factors for MTSS include an excessively pronated foot
53 when standing and excessive hindfoot eversion when running.^{1,5,9} Subjects with MTSS
54 exhibit greater hindfoot eversion than those without MTSS during forward steps and
55 running.^{10,11} Greater hindfoot eversion may lead to increased activity of the soleus,
56 flexor digitorum longus, and tibialis posterior muscles.^{1,9-11} A cadaver study reported
57 that tension of these muscles' tendons generated strain on the posteromedial border of
58 the tibia.¹² The increased contractions of these muscles, in turn, may create a traction
59 force on the posteromedial border of the tibia, causing inflammation. In addition, during
60 walking and running, foot pronation couple with internal rotation of the tibia may
61 generate bone torsional stress.^{13,14} Because the tibiae of healthy subjects were weak
62 against torsional stress, the tibia of subjects with MTSS may be subjected to large
63 torsional strain during excessive foot pronation.¹⁵ Therefore, an excessively pronated

64 foot in both static and dynamic alignments could be related to the development of
65 MTSS.

66 Previous studies reported that static pronated foot posture is characterized by
67 hindfoot eversion, forefoot inversion/eversion, abduction, and dorsiflexion.^{16,17} In
68 addition, hindfoot eversion is related to forefoot inversion, abduction, and dorsiflexion
69 during walking and running.^{13,14} Although greater hindfoot eversion is reported in
70 subjects with MTSS compared with those without MTSS during forward steps or
71 running,^{10,11} it is currently unclear where abnormalities in foot kinematics occur.
72 Kinematic changes of the forefoot and/or hindfoot may contribute to increased foot
73 pronation in people with MTSS. In the current study, we compared hindfoot and
74 forefoot kinematics during walking and running between subjects with and without
75 MTSS. We hypothesized that subjects with MTSS would exhibit significantly greater
76 forefoot inversion/eversion, abduction, dorsiflexion as well as hindfoot eversion and
77 abduction.

78

79 **2. METHODS**

80 The current study used a cross-sectional design, producing Level 3 evidence.
81 The subject groups were separated by the current presence or absence of disease and
82 examined for prior exposure of interest. This study was approved by the Ethical
83 Review Committee at the Faculty of Health Sciences, Hokkaido University, and
84 informed consent was obtained from all subjects.

85 *2.1. Subjects*

86 In total, 11 subjects with MTSS and 11 healthy controls (10 males and one
87 female in each group) participated in this study. All subjects belonged to a university
88 athletic club (Table 1). The diagnostic criteria for MTSS were: (1) tenderness at the
89 posteromedial border of the tibia, (2) a site of tenderness that spread over a minimum of
90 5 cm, and (3) no evidence of tibial stress fracture on plain radiographic images.^{1,4} An
91 experienced orthopedic surgeon (H.T.) diagnosed each subject with MTSS who had
92 experienced symptoms for at least 2 weeks. Exclusion criteria were: (1) any history of
93 fracture or surgery in the lower extremity or trunk, and (2) other injuries during the prior
94 3 months. None of the subjects complained of any symptoms except those associated
95 with MTSS, and all subjects reported that they were taking no medications for any
96 symptoms.

97 Pain severity at the tender area was assessed using a numeric rating scale. The
98 injured or more severely injured leg of the MTSS subject was used for analysis. The
99 control subject's leg was selected for analysis based on the ratio of the dominant and
100 non-dominant legs. The dominant leg was defined as the side used for kicking a
101 stationary ball.

102

103 2.2. *Data collection*

104 The arch height index and leg-heel angle while standing on both feet were
105 measured for static foot alignment.^{11,18} The arch height index was the ratio of the dorsal
106 height and truncated foot length.¹⁸ The dorsal height was taken at 50% of the total foot
107 length. The truncated foot length was the length from the posterior calcaneus to the first

108 metatarsal head. The leg-heel angle was the angle between the calcaneus midline and the
109 lower leg midline.¹¹ Each of these parameters was measured three times, then averaged.
110 The intraclass correlation values for intra-rater reliability were 0.941 for the arch height
111 index (95% confidence interval [CI] 0.512–0.988) and 0.804 for the leg-heel angle (95%
112 CI 0.349–0.952).

113 Subjects performed a static standing trial and two movement tasks: walking and
114 running barefoot on a treadmill. Subjects walked at a self-selected speed for 6 min and
115 ran at 12 km/hour for 3 min to become familiar with the treadmill's conditions.^{19,20} The
116 self-selected speed of walking was determined using a 10-m walking test. Subjects took
117 whatever rest time they needed between walking and running. Ratings of the perceived
118 exertion and pain severity during walking and running were recorded using a modified
119 Borg scale and the numeric rating scale, respectively.

120

121 *2.3. Data analysis*

122 Following familiar walking or running patterns, five consecutive strides were
123 recorded using EvaRT software (Motion Analysis Corporation, Santa Rosa, CA, USA)
124 with six digital cameras (Hawk cameras; Motion Analysis Corporation, Santa Rosa, CA,
125 USA) sampled at 200 Hz. Reflective markers were placed on the bony landmarks of the
126 thigh (greater trochanter and lateral epicondyle of the femur), shank, and foot based on
127 Leardini's foot model.²¹ Segment angles of the hindfoot relative to the shank and the
128 forefoot relative to the hindfoot were calculated using Visual 3D (C-Motion Inc.,
129 Germantown, MD, USA). All segment angles in the static standing position were set at

130 0° for each subject. These kinematic variables were normalized to 101 points of the
131 stance phase while walking and running.

132 For the walking task, the instant of initial contact (IC) and toe-off were
133 determined based on the acceleration of the calcaneus-based marker and the first
134 metatarsal head marker, respectively.¹⁹ For the running task, the strike pattern was
135 determined based on the time difference between the calcaneus and the fifth metatarsal
136 peak acceleration time.²² The rearfoot strike was defined as the point at which the peak
137 acceleration of the calcaneus marker was 15.2 ms earlier than that of the fifth metatarsal
138 marker, and the forefoot strike was defined as the point at which the peak acceleration of
139 the calcaneus marker was 5.49 ms later than that of the fifth metatarsal marker. The
140 midfoot strike was defined as a difference of 5.49–15.2 ms between the calcaneus and
141 fifth metatarsal markers. The IC was determined based on the acceleration of the
142 calcaneus marker for a rearfoot strike runner and that of the second metatarsal marker
143 for a midfoot or forefoot runner.²³ Toe-off during running in all subjects was determined
144 based on the maximum extension of the knee joint angle, which was calculated
145 according to the markers of the greater trochanter, lateral epicondyle of the femur, head
146 of the fibula, and lateral malleolus.¹⁹

147

148 *2.4. Statistical analysis*

149 The kinematic data were extracted at every five points from the normalized
150 stance phase. An independent t-test was performed to detect group differences in the
151 demographic data, static foot alignment, walking speed, modified Borg scale, and

152 kinematic data. All significance levels were set at $P < 0.05$. Statistical analyses were
153 performed using IBM SPSS Statistics version 17 (SPSS Inc., Chicago, IL, USA). In
154 addition, effect sizes (ESs) were calculated to indicate the magnitude of the differences
155 using G*Power 3.1 (Universität Kiel, Germany).

156

157 **3. RESULTS**

158 The MTSS group had significantly higher body mass index values ($P < 0.005$)
159 than the control group. There were no differences in the other demographic data, static
160 foot alignment, walking speed, or modified Borg scale (Tables 2, 3). No subject dropped
161 out of this study because of pain. The MTSS group had seven forefoot strikers and four
162 midfoot strikers. The control group had eight forefoot strikers and three midfoot strikers.
163 There were no rearfoot strikers in either group.

164 Analysis of the walking kinematics (Figure 1) showed that the MTSS group
165 exhibited significantly greater hindfoot eversion at IC ($P < 0.05$, ESs = 1.07) and
166 significantly greater abduction at IC and during 40%–60% of the stance phase ($P < 0.05$,
167 ESs = 0.73–1.10) compared with the control group. In addition, the MTSS group
168 exhibited significantly greater forefoot eversion at 80% ($P < 0.05$, ESs = 1.01) and
169 significantly greater abduction during 5%–85% ($P < 0.05$, ESs = 0.94–1.89) of the
170 stance phase than the control group. There were no significant differences in hindfoot or
171 forefoot dorsiflexion between the MTSS and control groups ($P > 0.05$).

172 Analysis of the running kinematics (Figure 2) showed that the MTSS group
173 exhibited significantly greater hindfoot eversion during 0%–15% and 75%–90% ($P <$

174 0.05, ESs = 0.98–1.34) and significantly greater abduction during 0%–20% and 70%–
175 100% ($P < 0.05$, ESs = 1.00–1.76) of the stance phase than the control group. In
176 addition, the MTSS group exhibited significantly greater forefoot abduction during
177 15%–40% and 70%–85% ($P < 0.05$, ESs = 0.96–1.11) of the stance phase than the
178 control group. There were no significant differences in hindfoot dorsiflexion or forefoot
179 eversion and dorsiflexion between the MTSS and control groups ($P > 0.05$).

180

181 **4. DISCUSSION**

182 The current results revealed that the kinematics of the hindfoot and forefoot
183 while walking and running were different between subjects with and without MTSS,
184 supporting our hypothesis that not only hindfoot but also forefoot kinematics during
185 walking and running were different between these two groups. The findings of our study
186 were consistent with the findings of previous studies investigating foot kinematics in
187 subjects with MTSS.⁹⁻¹¹

188 A previous prospective study reported that increased hindfoot eversion and
189 abduction during running were significant risk factors for MTSS.⁹ Moreover, hindfoot
190 eversion is correlated with forefoot abduction during walking and running.¹⁴ Therefore,
191 we propose that the changes in kinematics of the hindfoot and forefoot observed in our
192 study were more likely to be the cause than the result of MTSS. In addition, several
193 previous studies reported that a previous history of MTSS is a risk factor for further
194 MTSS.^{1,2,5} These findings indicate that MTSS involves factors that portend the further
195 development of MTSS. In the present study, subjects with MTSS exhibited greater

196 eversion and abduction in both the hindfoot and forefoot during walking and running,
197 which are factors that can contribute to the development of MTSS.

198 In the current study, subjects with MTSS exhibited greater hindfoot and
199 forefoot eversion and abduction during walking and running than subjects without
200 MTSS. The tibialis posterior originates from the posterior of the tibia and fibula and
201 attaches to the navicular, cuneiform, and second through the fourth metatarsal base.²⁴
202 The flexor digitorum longus and soleus originate from the posteromedial border of the
203 tibia, and attach to the distal phalanges of the foot and medial calcaneal tuberosity,
204 respectively.²⁴ The soleus is an inverter of the calcaneus.^{25,26} The increase in hindfoot
205 and forefoot eversion may contribute to the stretching of these muscles and tendons.
206 There may be more demand during contraction of these muscles in a more stretched
207 position in subjects with MTSS than in those without MTSS. This may then generate
208 greater traction force on the tibial fascia.^{11,12,26}

209 Subjects with MTSS exhibited greater hindfoot abduction relative to the shank
210 and greater forefoot abduction relative to the hindfoot, compared with subjects without
211 MTSS. Therefore, the foot was at an abducted position relative to the shank in MTSS.
212 This may indicate that the shank exhibits internal rotation relative to the foot, generating
213 tibial torsional stress. In addition, increased foot pronation, consisting of foot eversion,
214 abduction and dorsiflexion relative to the lower leg, would generate greater free
215 moment during the stance phase of running.²⁷ Subjects with MTSS in the present study
216 may exhibit increased shank internal rotation and greater free moment, which could
217 generate torsional stress on the tibia. Moreover, subjects with MTSS exhibited higher

218 BMI values than those without MTSS. Several previous authors assumed that higher
219 BMI values would increase loading on the tibia, causing stress when bending and/or
220 bowing.^{5,28} Thus, increased forefoot and hindfoot abduction and higher BMI values in
221 subjects with MTSS would be expected to generate greater loading on the tibia.^{5,27,28}

222 Subjects with MTSS had greater hindfoot and forefoot kinematics not only
223 when running, but also when walking. Thus, the tibias of individuals with MTSS may be
224 exposed to greater stress by traction force or free moment during activities of daily
225 living than those without MTSS. Such walking may delay alleviation of MTSS
226 symptoms and result in long rehabilitation periods before returning to sports
227 participation.^{6,7} Therefore, clinicians should correct the forefoot and hindfoot kinematics
228 of subjects with MTSS during both running and walking during their rehabilitation.
229 Several previous studies reported that augmented low-dye tape or induced contraction of
230 intrinsic foot muscles could decrease forefoot abduction and hindfoot eversion during
231 walking or sitting with a vertical load on the foot.^{29,30} Taping the foot or promoting
232 intrinsic foot muscle activity could be effective for modifying the forefoot and hindfoot
233 kinematics of MTSS.

234 Although most runners are classified as rearfoot strikers, our subjects were
235 classified as midfoot/forefoot strikers. It is unclear whether the results we observed
236 during running in midfoot/forefoot strikers are applicable to rearfoot strikers, because
237 the hindfoot kinematics during running were reported to be significantly different
238 between rearfoot and midfoot/forefoot strikers.³¹ Thus, further investigation will be
239 needed to confirm whether our results apply to rearfoot strikers. However, our findings

240 regarding hindfoot kinematics observed during running in midfoot/forefoot strikers with
241 MTSS were consistent with the results of previous studies of rearfoot strikers with
242 MTSS.^{9,11} Thus, we assumed that patients with MTSS exhibited greater hindfoot motion
243 during running, regardless of strike pattern. Furthermore, rearfoot strikers with MTSS
244 might have exhibited similar forefoot kinematics to those observed in the current study
245 during running because hindfoot motion is significantly correlated with forefoot motion
246 during running.¹⁴ Future studies should investigate multi-segmental foot kinematics in
247 rearfoot strikers with MTSS.

248 Our study involved several limitations that should be considered. First, because
249 we used a cross-sectional study design, we were unable to determine cause and effect. A
250 prospective study in the future may be useful for elucidating this issue. Second, our
251 study tasks comprised only walking and running. Athletes perform a wide range of other
252 movements, including jumping, side-cutting, and turning. Hence, the results of the
253 current study may not apply in the presence of other movements. Third, we did not
254 measure muscle activation of the soleus, flexor digitorum, and tibialis posterior muscles.
255 Activation of these muscles should be examined in future studies, to understand the
256 relationship between kinematics and MTSS. Fourth, subjects with MTSS exhibited
257 higher BMI values than those without MTSS. The higher BMI values may affect
258 forefoot and hindfoot kinematics. Several studies, however, reported that subjects with
259 MTSS exhibited increased foot pronation during walking, even though the BMI was not
260 significantly different between subjects with and without MTSS.^{32,33} These findings
261 suggest that the changes in foot kinematics of the MTSS subjects may not depend on

262 BMI values. Finally, we did not record the ground reaction force or calculate free
263 moment in our study. Future studies should investigate ground reaction force in subjects
264 with MTSS during walking and running.

265 In conclusion, the current findings revealed that forefoot and hindfoot eversion
266 and abduction differed between subjects with and without MTSS during walking. In
267 addition, subjects with MTSS had greater forefoot abduction and hindfoot eversion and
268 abduction during running than those without MTSS. For prevention and rehabilitation of
269 MTSS, it may be important to focus on not only hindfoot but also forefoot kinematics
270 during walking and running.

271

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275

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361 Figure legends

362 Figure 1. Kinematic waveforms during the stance phase of walking. Kinematic
363 waveforms of the hindfoot relative to the shank (a)–(c), and the forefoot relative to the
364 hindfoot (d)–(f). Dark gray boxes indicate the period of significant differences ($P <$
365 0.05) between the medial tibial stress syndrome group (MTSS) and matched control
366 group (Control).

367

368 Figure 2. Kinematic waveforms during the stance phase of running. Kinematic
369 waveforms of the hindfoot relative to the shank (a)–(c), and the forefoot relative to the
370 hindfoot (d)–(f). Dark gray boxes indicate the period of significant differences ($P <$
371 0.05) between the medial tibial stress syndrome group (MTSS) and matched control
372 group (Control).

373

1 Table 1 Distributions of sport-specific athletes in each group, number of training days
 2 per week, and main training sites

		MTSS (n=11)	Control (n=11)	Training days per week (days)	Main training site
	Short track	5	3	5	Ground
Track and field	Middle and long distance	1	4	5-6	Ground and Concrete
	Field	2	0	5	Ground
Tennis		2	4	3-4	Clay or grass court
Basketball		1	0	3-4	Gymnasium

3 MTSS: Medial tibial stress syndrome

4 Table 2 Demographic data

	MTSS group		Control group		<i>P</i> value
	Mean (SD)	95% CI	Mean (SD)	95% CI	
Age (years)	20.5 (1.5)	[19.5, 21.6]	20.5 (1.4)	[19.6, 21.5]	1.00
Height (cm)	170.7 (5.4)	[167.1, 174.4]	172.0 (5.6)	[168.0, 175.6]	0.66
Weight (kg)	64.3 (7.8)	[59.0, 69.5]	58.4 (7.2)	[53.5, 63.2]	0.08
BMI (kg/m ²) †	22.0 (2.0)	[20.7, 23.4]	19.7 (1.3)	[18.8, 20.6]	0.005
Arch height index	0.32 (0.02)	[0.30, 0.34]	0.31 (0.02)	[0.30, 0.33]	0.49
Leg heel angle (degree)	4.1 (1.8)	[2.9, 5.4]	3.7 (4.1)	[0.9, 6.4]	0.75

5 MTSS: Medial tibial stress syndrome, BMI: body mass index, 95% CI: 95% confidence

6 intervals, †: $P < 0.05$

7 Table 3 Walking speed, pain severity and modified Borg scale

		MTSS group		Control group		<i>P</i> value
		Mean (SD)	95% CI	Mean (SD)	95% CI	
Walking speed (km/hour)		5.0 (0.8)	[4.4, 5.5]	4.9 (0.8)	[4.4, 5.4]	0.83
Pain severity	Tenderness	4.2 (1.3)	[3.3, 5.0]	N.A	N.A	N.A
	Walking	0.0 (0.2)	[-0.1, 0.1]	N.A	N.A	N.A
	Running	0.7 (1.3)	[-0.1, 1.6]	N.A	N.A	N.A
Modified Borg scale	Walking	0.3 (0.5)	[0.0, 0.6]	0.3 (0.4)	[0.0, 0.5]	0.81
	Running	2.1 (1.6)	[1.1, 3.2]	1.3 (1.5)	[0.3, 2.3]	0.22

8 MTSS: Medial tibial stress syndrome, 95% CI: 95% confidence interval, N.A: not
9 applicable

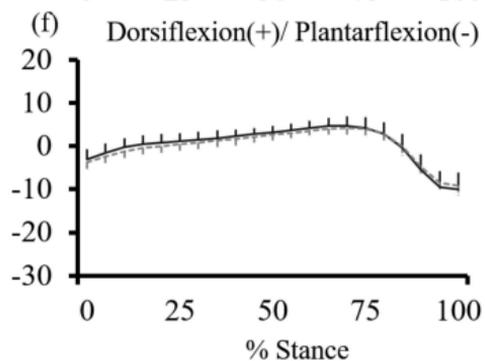
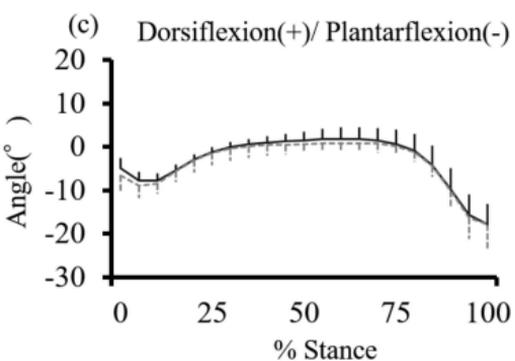
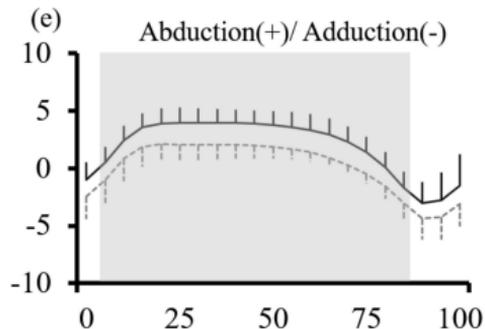
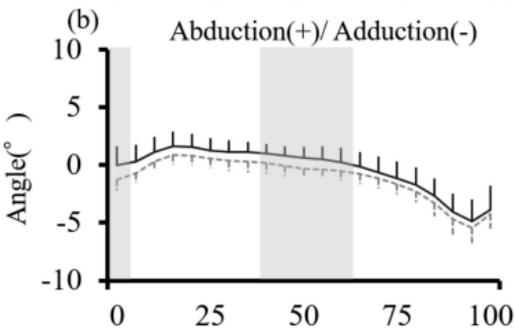
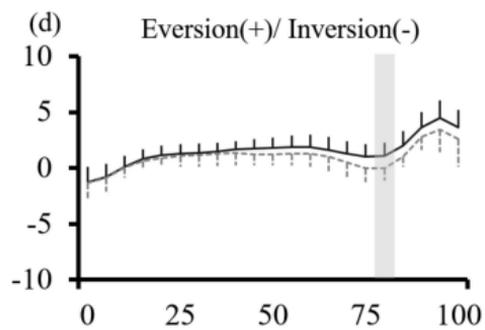
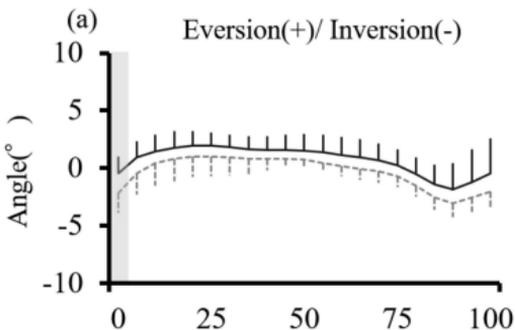
1 Figure 1. Kinematic waveforms during the stance phase of walking. Kinematic
2 waveforms of the hindfoot relative to the shank (a)–(c), and the forefoot relative to the
3 hindfoot (d)–(f). Dark gray boxes indicate the period of significant differences ($P <$
4 0.05) between the medial tibial stress syndrome group (MTSS) and matched control
5 group (Control).

6

7 Figure 2. Kinematic waveforms during the stance phase of running. Kinematic
8 waveforms of the hindfoot relative to the shank (a)–(c), and the forefoot relative to the
9 hindfoot (d)–(f). Dark gray boxes indicate the period of significant differences ($P <$
10 0.05) between the medial tibial stress syndrome group (MTSS) and matched control
11 group (Control).

Hindfoot

Forefoot



— : MTSS - - - - : Control

