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The Effects of Shoe Traction and Obstacle Height on Lower Extremity Coordination Dynamics during Walking

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1 **Abstract**

2 This study aims to investigate the effects of shoe traction and obstacle height on
3 lower extremity relative phase dynamics (analysis of intralimb coordination) during
4 walking to better understand the mechanisms employed to avoid slippage following
5 obstacle clearance. Ten participants walked at a self-selected pace during eight conditions:
6 four obstacle heights (0%, 10%, 20%, and 40% of limb length) while wearing two pairs of
7 shoes (low and high traction). A coordination analysis was used and phasing relationships
8 between lower extremity segments were examined. The results demonstrated that
9 significant behavioral changes were elicited under varied obstacle heights and frictional
10 conditions. Both decreasing shoe traction and increasing obstacle height resulted in a more
11 in-phase relationship between the interacting lower limb segments. The higher the obstacle
12 and the lower the shoe traction, the more unstable the system became. These changes in
13 phasing relationship and variability are indicators of alterations in coordinative behavior,
14 which if pushed further may have lead to falling.

15

16 *Keywords:* Dynamical systems theory, Shoe traction, Obstacle clearance, Locomotion.

17 **1. Introduction**

18 Injuries associated with slips, trips and falls continue to pose a significant burden
19 to society both in terms of human suffering and economic losses (Grönqvist & Roine,
20 1993; Kemmlert & Lundholm, 1998; Leamon & Murphy, 1995; Manning et al., 1988;
21 National Safety Council, 1995). According to statistics from the Health and Safety
22 Executive (HSE), slips and trips are the single most common cause of injuries at work,
23 and account for over a third of all major work injuries. In the US, falls accounted for 19%
24 of all nonfatal occupational injuries in 2001, and 13% of fatal occupational injuries in
25 2002 (Department of Health and Human Services, 2003). The annual direct cost
26 occupational injuries due to slips, trips and falls in the US has been estimated to be in
27 excess of 6 billion US dollars (Courtney et al., 2001), and a cause of serious public health
28 problem with costs expected to exceed \$43.8 billion by the year 2020 in the US alone
29 (Englander et al., 1996).

30 Both slips and trips result from unintended or unexpected changes in the contact
31 between the feet and the walking surface. Thus, conventional biomechanical analyses
32 (i.e. gait analysis) have been used to investigate human factors that cause slips, trips, and
33 falls and their complex interaction with environmental factors (Moyer et al. 2006;
34 Petrarca et al. 2006). Human factors include gait biomechanics, expectation, the health of
35 the sensory systems (i.e. vision, proprioception, and vestibular) and the health of the
36 neuromuscular system (Moyer et al. 2006). Among the most important environmental
37 factors that could potentially cause instability during walking are the presence of
38 obstacles and the loss of traction between the shoe sole and floor surface (Cohen &
39 Compton, 1982). Therefore, numerous studies have investigated the effect of obstacle

40 perturbations during walking (Begg et al., 1998; Chen et al., 1994; Chen and Lu, 2006;
41 Chou & Draganich, 1997; Jaffe et al., 2004; McFadyen & Prince, 2002; Patla et al., 1991;
42 Patla & Rietdyk, 1993; Petrarca et al., 2006; Sparrow et al., 1996). However, this
43 research has focused on the approach to an obstacle by collecting gait data of the trailing
44 and leading limb while negotiating the obstacle. In addition, there have been numerous
45 studies that have used biomechanics of gait to examine the shoe–floor interface to
46 understand slips (Burnfield & Powers, 2006; Bring, 1982; Cham & Redfern, 2001,
47 2002a, 2002b; Gao et al., 2003, 2004; James, 1980; Lockhart et al., 2003, 2005; Perkins,
48 1978; Perkins & Wilson, 1983; Redfern & Dipasquale, 1997; Strandberg, 1983;
49 Strandberg & Lanshammar, 1981; Winter, 1991). However, limited attention was devoted
50 to the combined effect of obstacles and low friction shoe–floor interface on the landing
51 strategies adopted to avoid slipping after obstacle clearance (Patla & Rietdyk, 1993;
52 Bentley & Haslam, 1998; Leclercq, 1999). Two main categories of adaptive strategies are
53 used when an individual encounters both an obstacle and a more slippery zone:
54 “*strategies of avoidance*” that consist of modifying walking patterns in order to step over
55 the obstacle, and “*strategies of accommodation*” that consist of the modification of
56 walking patterns in order to adapt to the low friction footwear-floor interface (Patla,
57 1991). The question thus arises: how these strategies interact and what kinds of corrective
58 reactions occur in an attempt to avoid a fall.

59 Conventional kinematic gait analysis of slip, trip, and fall events rely on angular
60 position-time, velocity-time, or angle-angle presentations (e.g. Cham & Redfern, 2001;
61 Fong et al., 2005). However, such presentations do not reveal the direct relationship
62 between velocity changes and position (Burgess-Limerick et al., 1993; Kurz et al., 2005;

63 Van Uden et al., 2003; Winstein & Garfinkel, 1989). It is important to evaluate this
64 relationship since the joint and muscle proprioceptors, and the visual and vestibular
65 receptors provide sensory feedback on both velocity and position. This means that the
66 multiple sensory cues will potentially compete for governance of the evoked behavioral
67 response (Misiaszek, 2006). Furthermore, quantification of interjoint (e.g., thigh-shank)
68 coordination is very difficult with the above-mentioned presentations (Burgess-Limerick
69 et al., 1993; Davids et al., 2003; Scholz, 1990; Scholz & Kelso, 1989; Sparto et al.,
70 1997). Coordination analysis using relative phase dynamics can solve the above problems
71 and provide a window of particular types of causal motor control processes that are not
72 usually revealed by conventional time-based plots (Gottlieb et al., 1983; Hamill et al.,
73 1999; Heiderscheit et al., 1999; Kurz et al., 2005; Kwakkel & Wagenaar, 2002; Sparto et
74 al. 1997; Van den Berg et al., 2000; Van Uden et al., 2003; Winstein & Garfinkel, 1989).
75 Relative phase dynamics utilizes the displacements and velocities of the segments that
76 surround a joint to quantify the joint's coordination. For example, the continuous relative
77 phase, a measure from relative phase dynamics, quantifies the coordination between the
78 shank and thigh segments that compose the knee joint. Such a measure is appealing for
79 quantifying signs of gait instability because it can reveal the compensatory reactions
80 evoked in the lower extremity coordination patterns that may be due to changing task
81 (obstacle clearance) and environmental (low friction) demands.

82 Therefore, the purpose of this study was to use a coordination analysis to
83 investigate the effects of shoe traction and obstacle height on lower extremity
84 coordination during walking to better understand the control strategies adopted to avoid
85 slippage following obstacle clearance in normal young adults. In this study, we examined

86 the intralimb phasing relationships between the foot, the shank and the thigh of the
87 landing limb (Kurz et al., 2005). We hypothesized that stepping over obstacles with low
88 shoe traction will challenge the motor control of the neuromuscular system and will
89 affect intralimb phasing relationships. In this study, obstacle height was adjusted to
90 percentages (0%, 10%, 20%, and 40%) of limb length to ensure that individuals of
91 different heights would make the same qualitative adaptation in going over obstacles.

92

93 **2. Methods**

94 **2.1. Participants**

95 Ten healthy young adult males between the ages of 18 and 35 from the general
96 student community of the University of Nebraska at Omaha volunteered as participants
97 (age: 25.8 ± 4.29 years; body mass: 82.8 ± 8.25 kg; height: 179.6 ± 6.34 cm; leg length —
98 as measured from the right anterosuperior iliac spine to the right lateral malleolus: $95.6 \pm$
99 4.49 cm; shoe size: 10). All participants were without appreciable leg length discrepancy
100 and had no injuries or abnormalities that would affect their gait. Prior to testing, each
101 participant provided an informed consent approved by the University of Nebraska
102 Medical Center Institutional Review Board.

103

104 **2.2. Instrumentation**

105 A sagittal view of the right lower extremity was obtained for all trials using a
106 Panasonic WV-CL350 (Osaka, Japan) video camera with a sampling frequency of 60 Hz.
107 The video camera was located 8-meter perpendicular to the walking pathway. A zoom
108 lens (COSMICAR TV, 8-48 mm zoom lens, COSMICAR/PENTAX Precision Co.,
109 Tokyo, Japan) was used in conjunction with the video camera to optimize image size and
110 minimize perspective error. A light source (Pallite VIII using eight ELH 300 W tungsten-
111 halogen projection lamps at 120 VAC) was mounted with the camera lens in the center of
112 the ring to better illuminate the reflective markers.

113 Reflective markers were positioned on the participant's right lower extremity,
114 here referred to as the leading limb (i.e. the limb crossing the obstacle first). All
115 positional markers were placed on the participants by the same examiner. Sagittal plane

116 marker placement was as follows: (1) mid-distance between the greater trochanter of the
117 hip and the lateral joint line of the knee, (2) lateral joint line of the knee, (3) lateral
118 malleolus, (4) outsole of the shoe approximately at the bottom of the calcaneus, and (5)
119 outsole of the shoe approximately at the fifth metatarsal head. An additional marker was
120 positioned at the obstacle to assist in determining the location of the obstacle in the field
121 of view.

122 The video images were stored on SVHS video tapes via a Panasonic AG-1970P
123 video camera recorder, which was interfaced with a Magnavox TV for an instant
124 qualitative evaluation of the video recording. The video data were transformed to digital
125 format and digitized via the PEAK MOTUS video system (Peak Performance
126 Technologies, Inc., Englewood, CO). A single camera was used because sagittal view
127 measures of walking correspond well in two- and three-dimensions (Doriot & Cheze,
128 2004; Eng & Winter, 1995). GRF data were also collected using a force platform. These
129 data were presented elsewhere (Houser et al., 2008).

130 Two pairs of men's shoes (Pro-wing Joggers, size 10), with homogenous midsoles
131 and rubber outsoles, were used in this experiment. The same shoes and shoe size were
132 used for all participants to minimize any effects from the shoe characteristics on the
133 results of the study. The shoe size of 10 was selected because it is the most common shoe
134 size among males in USA. To decrease the COF of one pair of the shoes, without
135 significantly modifying their weight, flexibility and general performance, 88 metallic
136 one-half inch diameter disc thumbtacks were inserted into the outsole of both the left and
137 right shoe. The thumbtacks were carefully placed in order to ensure that no part of the
138 actual shoe was able to contact the ground during walking locomotion. They were also

139 roughed and cleansed to expose the metal originally covered with enamel. The
140 thumbtacks increased the weight of the shoes by 25 g (475 g without the tacks vs. 500 g
141 with the tacks). The pair with the high traction had dynamic COF (DCOF) of 0.7 and
142 static COF (SCOF) of 0.8. The pair with the low traction had DCOF of 0.3 and SCOF of
143 0.35. The two selected tractions were based upon previous literature (Perkins, 1978;
144 Denoth, 1989) and test pilot work suggesting the high traction pair was a very safe shoe,
145 while the low a borderline safe shoe. Both high and low traction shoes were roughed with
146 20 passes of the 100 grit sand paper, and then the surfaces were cleansed with rubbing
147 alcohol to remove from the outsoles any solvents or residues of the shoe manufacturing
148 process.

149

150 *2.3 Experimental protocol*

151 Participants wore shoes provided by the investigator, and minimal clothing to
152 achieve correct positioning of reflective markers by using the anatomical landmark
153 points. They were given ample time to acclimate to the experimental set-up prior to
154 testing. Walking trials were conducted on a 30-meter level oval track with a 0.6 meter
155 wide lane; however, data were not recorded along the curved portion of the walkway.
156 Data collection was performed along the straight 10-meter walkway section of the track;
157 the force platform is embedded at the middle of this straight walkway. Walking speed
158 was monitored around the location of the force platform and over a 3-m interval using a
159 custom-made photocell timing system.

160 During familiarization, the investigator asked the participants if there was any
161 shoe discomfort that may alter their natural gait. If no problems were reported, the

162 participants proceeded in establishing a comfortable self-selected walking speed which
163 was recorded. Based upon the participant's self-selected walking speed, a range that
164 allowed $\pm 5\%$ deviation of this speed was used for the subsequent testing and a trial was
165 considered acceptable only when the walking speed was within this predetermined range.
166 The investigator also asked the participants not to look at the floor to locate the force
167 platform for proper right foot placement, as this could influence the participant's natural
168 walking. For this purpose, a foot placement marker was located approximately 7 m
169 before the force platform to allow for a normal right foot contact with the force platform.
170 This distance was determined through trial and error during the practice trials. Each trial
171 was visually monitored to insure that the stride was normal and the foot was completely
172 on the force platform. Data transfer from the cameras to the computer allowed for an
173 inter-trial rest interval of one minute.

174 All participants were asked to walk at their previously established self-selected
175 speed under four different obstacle conditions. The first condition was walking on a level
176 surface while the other three conditions were walking over obstacles of three different
177 heights. The average height of the obstacles was approximately: 8-10 cm (low, 10% leg
178 length), 18-20 cm (medium, 20% leg length) and 36-40 cm (high, 40% leg length). These
179 obstacle heights were established based upon pilot work, previous literature and obstacle
180 dimensions commonly encountered in the everyday environment (Chen et al., 1991; Chen
181 et al., 1994; Chou & Draganich, 1997; Patla et al., 1991; Patla & Rietdyk, 1993; Patla et
182 al., 1996). The 10% obstacle height characterizes door thresholds, the 20% obstacle
183 height represents typical curbstones separating cars in parking lots and stair risers, and
184 40% obstacle height corresponds to bathtub rims, where frequent falls occur especially

185 among the elderly. The obstacles were placed directly before the force platform so that
186 the participant had to clear the obstacle with the right leg and land on the force platform.
187 The obstacles were made of light weight wood so that if a participant stepped on or hit
188 the obstacle by mistake while walking, the obstacle was destroyed. This minimized the
189 risk of tripping and falling. All participants were required to complete the baseline and
190 obstacle conditions with the two pairs of shoes (high and low traction outsole) as
191 described previously.

192 Each experimental condition (shoe traction \times obstacle) consisted on ten trials for a
193 total of eighty trials per participant. The order of the presentation of conditions was
194 predetermined as follows: (1) low traction – 0%; (2) low traction – 10%; (3) low traction
195 – 20%; (4) low traction – 40%; (5) high traction – 0%; (6) high traction – 10%; (7) high
196 traction – 20%; (8) high traction – 40%. Furthermore, participants were given several
197 practice trials prior to each condition to familiarize themselves with the task and the
198 environmental constraints.

199

200 *2.4 Data reduction and analysis*

201 Kinematic data were analyzed during the stance period only. All kinematic
202 coordinates were scaled and smoothed using a Butterworth low-pass filter with a
203 selective cut-off algorithm based on Jackson (1979). The cut-off values were 8-14 Hz.
204 Subsequently, from the planar coordinates, foot, shank, and thigh angular displacements
205 were calculated in a counter-clockwise direction relative to the right horizontal axis.
206 From the angular displacements, the angular velocities were calculated using a finite
207 difference approach. All kinematic angular displacements and velocities were normalized

208 to 100 points for the stance period using a cubic spline routine to enable mean ensemble
209 curves to be derived for each participant and for each condition. The touchdown and toe-
210 off timing occurrences as well as the transition time (crossover) from braking to
211 propulsion were identified from the anterior-posterior ground reaction force data using
212 laboratory software. Since the kinetic and kinematic data files were time matched, the
213 time of the transition (crossover) from braking to propulsion was used to evaluate each
214 footfall for two periods: (1) heel contact to transition (absorption or braking period) and
215 (2) transition to toe-off (propulsion period). It was decided to divide the stance period at
216 the transition time (crossover) from braking to propulsion for two main reasons: (1) this
217 event separates the absorption and propulsion periods, during which different kinematic
218 strategies may exist (Bates et al.,1978), (2) the measurements over the entire stance can
219 mask differences for a single period (Byrne et al., 2002).

220 The angular kinematic data were then subjected to a coordination analysis (Kurz
221 & Stergiou, 2004a, 2004b, 2004c; Kurz et al., 2005; Scholz, 1990; Stergiou, 2001a,
222 2001b). Phase portraits for the sagittal foot, shank and thigh were generated. A phase
223 portrait is a plot of a segment's angular displacement *versus* its angular velocity (Barela
224 et al., 2000; Winstein & Garfinkel, 1989). The angular displacements and velocities were
225 normalized to their maximum absolute values (Van Emmerik & Wagenaar, 1996; Kurz &
226 Stergiou, 2004c). The resulting phase plane trajectories were then transformed from
227 Cartesian (x, y) to polar (r, θ) coordinates, where the radius was $r = (x^2 + y^2)^{1/2}$ and the
228 phase angle was $\theta = \tan^{-1} [y/x]$ (Kurz & Stergiou, 2002; Kurz et al., 2005; Rosen, 1970).
229 Phase angles calculated from these trajectories had a range of 0° to 180° . Phase angles
230 allow for the incorporation of angular displacements and velocities to examine

231 coordinative strategies. Subsequently, the normalized phase angles were used to
232 determine the phasing relationships between the segments. The foot and the shank can be
233 viewed as respectively rotating clockwise and counterclockwise around the ankle joint
234 axis, while the shank and the thigh can be viewed as rotating clockwise and
235 counterclockwise around the knee joint axis. Continuous relative phase represents the
236 phasing relationships or coordination between the actions of the two interacting segments
237 at every point during a specific time period (i.e., it depicts how the two segments are
238 coupled in their movements while performing the task) (Barela et al., 2000; Hamill et al.,
239 1999; Heiderscheit et al., 1999, 2000; Kwakkel & Wagenaar, 2002; Scholz, 1990).
240 Relative phase was calculated throughout the stance period by subtracting the phase
241 angles of the corresponding segments:

$$242 \Phi_{\text{SAGITTAL ANKLE RELATIVE PHASE}} = \Phi_{\text{FOOT}} - \Phi_{\text{SHANK}}$$

243 and

$$244 \Phi_{\text{SAGITTAL KNEE RELATIVE PHASE}} = \Phi_{\text{SHANK}} - \Phi_{\text{THIGH}}$$

245 Values close to 0° indicate that the two segments are moving in a similar fashion or in-
246 phase. Values close to 180° indicate that the two segments are moving in opposite
247 directions or out-of-phase. The relative phase curves for each segmental relationship
248 (ankle and knee) were averaged across trials, and mean ensemble curves were generated
249 for each participant for all conditions. The participant mean ensemble curves were also
250 averaged to generate group mean ensemble curves for all conditions. However, to
251 statistically test differences between relative phase curves, it was necessary to
252 characterize the curves by single numbers. Therefore, two additional parameters were
253 calculated using the participant mean ensemble curves (Byrne et al., 2002; Hamill et al.,

254 1999; Heiderscheit et al., 1999, 2000; Kurz & Stergiou, 2004b, 2004c; Stergiou et al.,
255 2001a, 2001b; Van Emmerik & Wagenaar, 1996).

256 The first parameter was the mean absolute value of the ensemble relative phase
257 curve values (MARP). This parameter was calculated by averaging the absolute values of
258 the ensemble curve points for the designated periods (stance, absorption and propulsion):

$$259 \quad MARP = \frac{\sum_{i=1}^N |\phi_{RelativePhase}|}{N}$$

260 where N is the number of points in the relative phase mean ensemble. Functionally, a low
261 MARP value indicated that the oscillating segments have a more in-phase coordinated
262 relationship; a high MARP value indicates that the oscillating segments have a more out-
263 of-phase coordinated relationship.

264 The second parameter was the deviation phase of the relative phase for the two
265 interacting segments provides a measure of stability of the neuromuscular system.
266 Deviation phase was calculated by averaging the standard deviations of the ensemble
267 relative phase curve points for the designated periods (stance, absorption and propulsion):

$$268 \quad DP = \frac{\sum_{i=1}^N |SD_i|}{N}$$

269 where N is the number of points in the relative phase mean ensemble and SD is the
270 standard deviation of the mean ensemble at the i^{th} point. Functionally, a low DP value
271 indicates a more stable organization of the neuromuscular system (i.e., a less variable
272 relationship between the two segments' actions); a high DP value indicates less stability
273 in the organization of the neuromuscular system.

274

275 **2.5. Statistical treatment**

276 Group means and standard deviations were calculated for MARP and DP for each
277 segmental relationship, for each period, and for each condition. A two-way repeated
278 measures ANOVA (shoe traction \times obstacle) was performed on the group means for
279 MARP and DP. Statistical analysis was performed for each coordinative relationship
280 (foot-shank and shank-thigh) and for each period (stance, absorption and propulsion). In
281 tests that resulted in significant F -ratios ($P < 0.05$), post-hoc analysis was performed
282 using Tukey tests.

283

284 **3. Results**

285 The shank-thigh (S-T) MARP group results were statistically significant for both
286 factors (shoe traction × obstacle) during all the three periods (stance, braking, and
287 propulsion; Tables 1 and 2). The S-T MARP values were significantly larger for the high
288 traction shoe, and decreased as the obstacle height increased in both shoes. Specifically,
289 the decrease in the S-T MARP values was symmetrical between obstacle conditions for
290 the stance and the propulsive periods in both shoes. However, for the braking period this
291 decrease was only noticeable from the level walking to the 10% obstacle conditions; the
292 post-hoc analysis showed no statistical differences between the obstacle conditions.
293 Regarding the foot-shank (F-S) MARP group results, no statistically significant
294 differences were found between conditions.

295 [Insert Tables 1 and 2 about here]

296 The DP group results were statistically significant for both S-T and F-S segmental
297 relationships for all three periods analyzed regarding the obstacle factor (Tables 1 and 2).
298 For the shoe factor all S-T segmental relationships were significant, while for the F-S
299 only the propulsive period was significantly different. All the DP group results increased
300 in value as the obstacle height increased for both shoes. Furthermore, the S-T DP results
301 were larger for the low traction shoes for all periods.

302 Graphically, the thigh segment during the stance phase showed a segmental
303 reversal which occurs towards the later part of stance (Figure 1a). Functionally, every
304 time that a trajectory goes through zero a segmental reversal is observed. It is worth
305 noting that the thigh exhibited a fairly constant velocity during the middle part of the
306 stance period, especially in the no obstacle conditions. Constant velocity is depicted by

307 flat horizontal sections. However, spatial aspects of the phase portraits expressed the
308 same general shape from one condition to the next. However, in level-walking (0%
309 obstacle) and low-obstacle (10%) conditions, low traction shoes caused an additional
310 curve segment to be developed within the original pattern during late stance. The shank
311 segment phase portraits revealed no reversals, indicating a backward only rotation around
312 the knee joint during the stance phase of walking (Fig. 1b). However, the foot behaved
313 differently than the other lower extremity segments (Fig. 1c). The foot segment during
314 stance displayed a cusp shape. Cusps in the foot trajectory path, when the velocity is near
315 zero, indicate sudden interruption in the movement pattern. This is due to the fact that the
316 foot remained flat on the ground for a period of time during midstance. The foot
317 trajectories were more similar geometrically between conditions; however, the angular
318 velocity of the foot segment appeared to increase during the later part of the stance period
319 in the high traction condition, as compared to the low traction situation. This observation
320 was graphically visible through a more pronounced concave-down configuration during
321 the later portion of the stance phase.

322 [Insert Figure 1 about here]

323 The group mean ensemble foot-shank (F-S) and shank-thigh (S-T) relative phase
324 curves for the stance period are displayed in figure 2. In general, it can be observed that
325 segmental relative phase relationships are non linear i.e., neither in-phase ($\sim 0^\circ$ values) nor
326 out-of-phase ($\sim 180^\circ$ values) by a constant magnitude during stance. In addition, during
327 level-walking, F-S and S-T relative phases began differently than for obstacle conditions.
328 Indeed, both segmental relative phases began around 0° for the no obstacle conditions,
329 whereas F-S relative phase began around -25° and S-T relative phase around $+50^\circ$ for the

330 obstacle conditions. Therefore, the effect of the obstacle on the relative phase caused the
331 segments to be more out of phase at touchdown.

332 The group mean ensemble F-S relative phase curves had similar configurations
333 for all conditions (Figure 2a). All curves began with negative values (or negative zero
334 values for the level-walking conditions) that indicated that the shank was leading the foot
335 (i.e., the shank was moving faster in phase space) during the first initial portion of stance.
336 Early in stance, the relationship between the foot and shank reversed. Reversal in the
337 relationship between the two segments was evident by the local minimum in the relative
338 phase graph. The positive slope after the local minimum indicated that the foot was
339 leading the shank segment (i.e., the foot was moving faster in phase space). During mid-
340 stance, the foot-shank relationship became more out of phase, and the foot clearly was
341 leading the shank (positive values: 25-50°). Moreover, there was not a distinct (unique)
342 local maximum in the F-S relative phase. In fact, inspection of the F-S relative phase
343 curve indicated that there were multiple fluctuations during midstance. Local minimums
344 and maximums suggest a change in direction of the relationship between the two
345 segments. During the late portions of the stance, the relationship between the foot and
346 shank became progressively in-phase.

347 The group mean ensemble S-T relative phase curves also displayed quite similar
348 trends (Figure 2b). For the obstacle conditions, all curves began with positive values that
349 indicated that the shank was leading the thigh. Immediately after the shank-thigh
350 relationship became more in-phase (0°) during mid-stance. During late stance, the
351 relationship between the shank and thigh became progressively out of phase with the
352 thigh leading. A slightly different segmental relationship occurred for the level-walking

353 conditions. As previously mentioned, the S-T segments began more in-phase (i.e., close
354 to zero degree). However, early in stance the relative phase became more-out-of-phase
355 with the thigh leading the shank before returning to a more in-phase relationship
356 throughout the middle portion of the stance period. During late stance, the relationship
357 became progressively out of phase, similarly to what was observed in the obstacle
358 conditions.

359 [Insert Figure 2 about here]

360

361 **4. Discussion**

362 Both our graphical and statistical results revealed that stepping over obstacles of
363 different height with shoe of varied traction may affect the motor control of the
364 neuromuscular system and will affect intralimb phasing relationships. The partitioning of
365 the stance period assisted in further understanding the strategies used and better evaluate
366 the results functionally.

367 Specifically, the phasing relationship between the foot and the shank segments
368 was not affected by either shoe traction or obstacle height changes. Graphically,
369 ensemble curves displaying the F-S relative phase support this statistical result (Fig. 4a).
370 However, the more in-phase relationship observed at initial foot contact in walking-level
371 conditions did change to become more out-of-phase in obstacle conditions. Furthermore,
372 early in stance, the magnitude of the curves' concavity was more prominent when the
373 obstacle height was increased. Even though these differences were not found to be
374 significant, probably due to the large similarities of the curves throughout the remaining
375 portion of the braking and the stance periods, they may be important due to the increased
376 danger of slipping during the braking period. Indeed, according to Perkins (1978), the
377 most dangerous slipping is most likely to occur in this period due to a low initial vertical
378 ground reaction force (GRF) at heel strike, which produces a small amount of friction. If
379 friction is not sufficient during the braking period, an anterior slip of the foot would
380 likely occur. This slip could be particularly dangerous due to the rapid transfer of weight
381 to the landing foot.

382 Contrary to F-S, S-T MARP showed significant differences for both factors
383 during all periods. The introduction of low traction shoes had as a result a more in-phase

384 relationship. Furthermore, the increasing obstacle height resulted in a more in-phase
385 relationship for both shoes. Thus, it seems that both independent variables affected the
386 coordinative behavior of the system at the knee. The more in-phase S-T segmental
387 relationship may indicate a tendency towards a behavioral change that eventually could
388 result in the emergence of a new behavioral state (i.e., slipping and/or falling). Therefore,
389 this relationship deserves more attention in future ergonomics studies that further want to
390 explore the relationship between shoe-floor traction following obstacle clearance.

391 In the present study, stability of the coordinated relationship between the two
392 interacting segments was measured by DP which describes the variability of the relative
393 phase. An interesting observation is that the increases in obstacle height resulted in
394 significantly increased F-S DP values. Thus, even though the F-S relative phase remained
395 similar (as indicated by the lack of differences for F-S MARP values), the F-S DP
396 increased significantly as the obstacle height increased. This result can be explained as an
397 increased instability based on the theoretical premises of the coordination analysis
398 performed (Kurz & Stergiou, 2004b). For the shoe traction factor, only F-S DP values
399 during propulsive period showed significant differences. The fact that DP increased for
400 the F-S segmental relationship in the low traction shoes indicates instability and lack of
401 coordination at the ankle joint during the propulsive period. This is further supported by
402 the fact that the smaller F-S DP values during propulsion were present at the high traction
403 conditions, which theoretically means that when the system is under normal preferred
404 conditions (normal walking) it would be highly stable. Furthermore, the S-T DP
405 increased as the obstacles height increased for both shoes in all periods. Moreover, the
406 low traction shoe had generally larger S-T values. These findings further supported the

407 hypothesis that increased instability would be present when the obstacle height and shoe
408 traction changed and became more unsafe.

409 Previously, angle-angle diagrams have been used to depict the organization of the
410 multiple degrees of freedom needed to complete one walking gait cycle (Grieve, 1968),
411 and several investigators have suggested methods for quantifying the coordination that is
412 qualitatively observable in these relative patterns (Sidaway et al., 1995; Sparrow et al.,
413 1987; Whiting and Zernicke, 1982). However, quantitatively understanding the control
414 mechanisms cannot be achieved with this methodology alone (Burgess-Limerick et al.,
415 1993). The usage of phase portraits and subsequently of relative phase, allows the
416 incorporation of both angular displacement and velocity to examine coordination and
417 movement (Kurz & Stergiou, 2004a, 2004b, 2004c; Kurz et al., 2005; Kwakkel &
418 Wagenaar, 2002; Scholz, 1990). Functionally, this approach is advantageous since there
419 is evidence that receptors exist within the muscles and tendons for controlling both
420 displacement and velocity (McCloskey, 1978). This is a particular strength of the present
421 study.

422 However, we should also consider several limitations of our study. First and most
423 importantly, the sample procedure lacks randomization. Indeed, from a practical and
424 methodological point of view randomization was in fact difficult to achieve. Because the
425 participants knew the shoe condition, it was not possible to eliminate the awareness of a
426 potential slip/fall (while wearing shoes with low friction) or trip/fall (while avoiding
427 obstacles). Accordingly, some caution with regard to generalization of the results must be
428 taken due to the lack of randomization. On the other hand, in our pilot work we found
429 that the order of the testing conditions did not reveal significant learning effects.

430 Additionally, participants were given one or more practice trials prior each condition to
431 familiarize themselves with the task and the environmental constraints. Our results in
432 terms of gait adaptations are also in agreement with those found in the literature (obstacle
433 clearance strategies: e.g. Begg et al., 1998; Chen et al., 1991; corrective reactions to slip
434 events: e.g. Perkins, 1978; Frederick, 1993; Cham & Redfern, 2001).

435 A second limitation of the present study is the extent to which the findings can be
436 generalized, as it is not possible to know how the laboratory slipping responses differed
437 from those that occur in a non-laboratory environment (Brady et al., 2000). It has been
438 proven that reproducing the unexpected nature of real-life slip, trip, and fall accidents in
439 laboratory settings is quite difficult. Therefore, the conclusions reported here underline
440 the importance of being conservative when applying research findings from slip, trip, and
441 fall experiments using human participants to design criteria of environmental safety (e.g.
442 friction requirements).

443 However, the findings of this investigation can provide the necessary foundation
444 to further investigate the coordinative control strategies utilized in more challenging
445 environments that may actually be associated with slips and falls. Additionally, further
446 investigation should be conducted to explore the anticipatory intralimb coordinative
447 strategies leading up to the stance phase of gait, as such adaptations could be critical in
448 order to successfully avoid slips, trips, and eventual falls. From an ergonomic
449 perspective, such investigations can have crucial implications to slip, trip, and fall injury-
450 prevention strategies in occupational and non-occupational environments, and how a
451 potentially hazardous situation is perceived.

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5. Conclusions

Our approach provided information to understand how young healthy adults change their gait to reduce the likelihood of a slip following clearance of obstacles of varied heights and landing with shoes of low traction. The changes in phasing relationship and variability are possible indicators of alterations in coordinative behavior, which may emerge to reduce the risk to the participant when confronted with an environment characterized by low traction and high obstacles. Changes do not suggest that falling or slipping did or will occur. However, if shoe traction and/or obstacle height would have been more extreme, falling may have occurred. Qualitative analysis during data processing did reveal that slippage occurred at initial foot contact. This slippage was of the type “slip-sticks” as described by Standberg and Lanshammar (1981). These slips never resulted in obvious postural or upper extremity adjustments. Slipping also occurred late in the propulsive period just prior to toe-off. This slipping was of little consequence, due to majority of weight acceptance to the opposing limb (Perkins, 1978).

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6

1 **Figure Captions**

2

3 Figure 1. Phase portraits (or phase planes) of the sagittal foot (a), shank (b), and thigh (c)
4 motions from a representative trial for all conditions during stance. Black solid lines: low
5 traction shoes; grey solid lines: high traction shoes.

6

7 Figure 2. Relative phase curves for the sagittal foot-shank (a) and shank-thigh (b)
8 segmental relationships from the same representative trial for all conditions during stance.
9 Each curve is an ensemble average over all trials. The standard deviation curves are not
10 represented on the graphs. Black solid lines: low traction shoes; grey solid lines: high
11 traction shoes. Heel contact occurs at 0% of the stance phase, and toe-off occurs at 100% of
12 the stance phase.

Table Captions

Table 1. Group means (M) and standard deviations (SD) for MARP and DP.

MARP: Mean Absolute value of the ensemble Relative Phase; DP: Deviation Phase of the relative phase). The values (in degrees) presented are for each coordinative relationship (F-S: foot-shank and S-T: shank-thigh) and for each period (stance, braking, and propulsion).

* : significantly different between shoes within the same obstacle height ($p < 0.01$).

† : significantly different between shoes within the same obstacle height ($p < 0.05$).

^{10,20,40%} : significantly different between obstacle heights within the same shoe ($p < 0.01$).

Table 2. F-ratios from the two-way ANOVA with repeated measures on both factors: shoe traction (s) \times obstacles (o). MARP: Mean Absolute value of the ensemble Relative Phase; DP: Deviation Phase of the relative phase; F-S: foot-shank; S-T: shank-thigh. Fs: between shoes; Fo: between obstacles; Fs \times o: interaction.