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Foot orthotics affect lower extremity kinematics and kinetics during running

Anne Mündermann [a,*], Benno M. Nigg [a], R. Neil Humble [b], Darren J. Stefanyshyn [a]

[a] *Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, 2500 University Drive NW, Calgary, Alta., Canada T2N 1N4*
[b] *Division of Podiatry, Faculty of Medicine, University of Calgary, Canada T2N 1N4*

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Abstract

Objective. To quantify the effects of posting and custom-molding of foot orthotics on lower extremity kinematics and kinetics during running.

Design. Repeated measures.

Background. Several kinematic and kinetic factors have been suggested to increase a runner's risk for injuries. It has been speculated that foot orthotics can be used to reduce injury related complaints or even prevent running injuries by affecting these factors.

Methods. Twenty one volunteers participated in this study. Kinematic and kinetic variables obtained during overground running for medial posting, custom-molding, and the combination of medial posting and custom-molding of foot orthotics were compared to a control condition. Repeated measures ANOVA and student *t*-tests were used to detect significant differences ($\alpha = 0.05$).

Results. Posting of foot orthotics reduced maximum foot eversion and ankle inversion moment and increased vertical loading rate and maximum knee external rotation moment ($P < 0.05$). Molding and posting and molding reduced vertical loading rate and ankle inversion moment and increased maximum foot inversion and maximum knee external rotation moment ($P < 0.05$).

Conclusions. The effects of posting and molding of foot orthotics are extremely different and when combining posting and molding, the effects of molding appear to be dominant. It yet remains to be determined whether posting or molding is more beneficial with respect to overuse running injuries.

Relevance

The potential of foot orthotics for reducing pain and injuries is convincing. The current study provides valuable information about the role of specific structural components of foot orthotics and contributes to the knowledge about the mechanism underlying the effect of foot orthotics in running.

Keywords: Foot orthotics; Kinematics; Joint moments; Loading rate; Running

1. Introduction

Custom-molded orthotics have been proposed as an effective treatment of running injuries and their efficacy is reflected in the reported success rates of fifty to ninety percent (Eggold, 1981; Dugan and D'Ambrosia, 1986; D'Ambrosia, 1985; Kilmartin and Wallace, 1994). However, it is not well understood why foot orthotics lead to an improvement of medical conditions. Several factors have been suggested to increase a runner's risk for injuries, including excessive pronation or foot eversion and foot eversion velocity (Messier and Pittala, 1988), increased internal tibia rotation (Nigg et al., 1993), increased impact peak and loading rate of the vertical ground reaction force (Hreliac et al., 2000), increased ankle inversion moments (McClay, 2000), and increased knee abduction and external rotation moments (Stefanyshyn et al., 1999). It has been speculated that foot orthotics can be used to reduce injury related complaints or even prevent running injuries by affecting

* Corresponding author.
E-mail address: ahau@kin.ucalgary.ca (A. Mündermann).

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these factors (Gross and Napoli, 1993; Eng and Pierrynowski, 1994; Nawoczenski et al., 1995; Nigg et al., 1988; Nigg et al., in press).

However, earlier studies found small and frequently not significant differences in kinematic variables when comparing different orthotic conditions (Eng and Pierrynowski, 1994; Nawoczenski et al., 1995; Smith et al., 1986; Novick and Kelley, 1990; Baitch et al., 1991; Stacoff et al., 2000) and, thus, it has been suggested that reducing foot eversion and tibia rotation may not be the primary function of foot orthotics (Hreliac et al., 2000). On the other hand, it has recently been shown that resultant joint forces and especially joint moments at the knee joint may be altered substantially (more than 100%) when using posted orthotics during running (Nigg et al., in press). McClay (2000) speculated that increased inversion moments at the ankle joint may be related to increased foot eversion. Therefore, it is speculated that reducing ankle and/or knee joint moments is an important function of foot orthotics.

Foot orthotics usually consist of different structural components including a neutral shell that is fabricated by molding a polypropylene shell to a positive mold of the foot and posting that is adding material to the medial or lateral aspect of the foot orthotics. Posting of molded orthotics has been claimed to increase the effects of foot orthotics. To improve the understanding of how foot orthotics affect lower extremity kinematics and kinetics, it is necessary to identify the function of these orthotic components.

Therefore, the purpose of this study was to quantify the effects of posting and custom-molding of foot orthotics on lower extremity kinematics and kinetics during running. It was hypothesized that (a) the effects of custom-molding and posting on ankle joint kinematics are small and unsystematic, (b) custom-molding and posting reduce ankle and knee joint moments, and (c) custom-molding and posting reduce the loading rate of the vertical ground reaction force during running.

2. Methods

Twenty one volunteers participated in this study (12 female, 9 male; Table 1). Prior to their participation, all subjects gave informed written consent according to the guidelines of The University of Calgary Ethics Committee.

2.1. Subject population

All subjects had no history of lower extremity injuries and none of the subjects had previously worn foot orthotics. Subjects were initially screened for weekly mileage (15–40 km/week) and two-dimensionally measured foot eversion during running at 4 m/s in the control condition on a treadmill (angle between heel bisection line and shank bisection line: >13°) (Clarke et al., 1984) and were thus classified as 'pronators' (Table 1). Range of motion of the joints and strength and flexibility of the muscles of the lower extremities measured manually were required to lie within normal values. Leg length discrepancy was measured as the distance between the anterior superior iliac spine and the medial malleolus with the subject lying supine and was required to be less than 0.5 cm for all subjects as assessed by one of the authors, RNH. The inclusion criteria in this study matched the criteria for the prescription of foot orthotics generally used by podiatrists.

Table 1
Subject information for 21 subjects: average (SD)

Maximum foot eversion in frontal plane (control condition); (°)		16.2	(3.2)
Minimum		13.1	
Maximum		25.4	
Age (years)		25.4	(5.6)
Weight (kg)	Male	65.0	(6.8)
	Female	63.7	(7.5)
Height (cm)	Male	174.2	(7.3)
	Female	167.2	(4.4)

2.2. Footwear

All experiments were performed using running sandals (Model: Bryce Canyon; The Rockport Company, Canton, MA, USA). The use of running sandals allowed for marker placement directly on the skin surrounding the calcaneus. The original inserts of the running sandals were removed and replaced by each of four insert conditions (Fig. 1; Table 2); the top layer of all orthotic conditions consisted of 3 mm Spenco (Spenco Medical Corporation, Waco, TX, USA). The molding condition was posted intrinsically to calcaneus neutral and the posting and molding condition was posted extrinsically. Both custom-molded conditions were fabricated with the goal to reduce maximum pronation.

2.3. Testing procedure

Subjects completed two weeks of their regular running schedule in the control condition (running sandal plus control insert). Following this initial phase, each subject was tested three times per week for three weeks (nine sessions per subject). In each of the nine sessions, subjects ran 200 m on an indoor running track with each of the four insert conditions. Subjects were then set up for biomechanical testing at the Human Performance Laboratory at the University of Calgary. The four insert conditions were tested in randomized order. However,

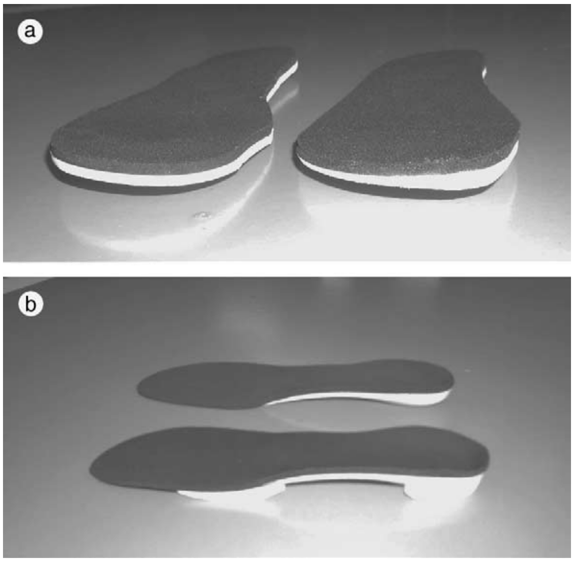

Fig. 1. Orthotic conditions used in this study: (a) control (left) and medial post (right); (b) neutral shell (top) and custom-orthotics (bottom).

Table 2
Material and geometric components of foot orthotics

Insert condition	Bottom layer	Shape	Posting
Control insert	EVA[a] (3 mm)	Flat	None
Medial post (posting)	EVA[a]	Flat	6 mm (medial; rearfoot and forefoot)
Neutral shell[b] (molding)	Polypropylene shell	Custom-molded	None
Custom-orthotics[b] (posting and molding)	Polypropylene shell	Custom-molded	6 mm (medial; rearfoot and forefoot)

The top layer of all conditions consisted of 3 mm Spenco©.
[a] Ethylene vinyl acetate (Solflex [shore C: 50-55], Phoenix AZ, USA).
[b] Paris Orthotics Ltd., Vancouver, Canada.

before testing each of the three orthotic conditions subjects ran 50 m in the control condition. Kinematic and kinetic data were collected for twelve running trials at 4.0 ± 0.2 m/s (heel–toe running; 48 trials per subject per session; total: 9072 trials).

2.4. Kinematic and kinetic data

Three reflective skin markers (diameter: 12.7 mm) were attached to each of the three segments of the lower extremity (thigh, shank, and foot, respectively) using medical adhesive spray (Hollister Incorporated, Libertyville, IL, USA). Additional joint markers were placed on the anterior superior iliac spine and the greater trochanter, the lateral epicondyle and the patella center, and the lateral malleolus and the insertion of the Achilles tendon to determine hip, knee and ankle joint centers, respectively. Joint coordinate systems (Cole et al., 1993) were constructed using the positional information of the segment and joint markers during a standing trial in the control condition.

Kinematic data were collected using seven high-speed cameras (240 Hz; Motion Analysis Corporation, Santa Rosa CA, USA). Three-dimensional marker traces were

Table 3
Lower extremity kinematic and kinetic variables and their definitions

Symbol	Variable name	Definition
$\beta_{ev,max}$	Maximum foot eversion	Maximum eversion angle about the long axis of the foot segment
$\beta_{inv,max}$	Maximum foot inversion	Maximum inversion angle about the long axis of the foot segment
θ_{max}	Maximum tibia rotation	Maximum angle about the longitudinal axis of the shank segment
$\beta'_{ev,max}$	Maximum foot eversion velocity	Maximum angular eversion velocity about the long axis of the foot segment
$\beta'_{inv,max}$	Maximum foot inversion velocity	Maximum angular inversion velocity about the long axis of the foot segment
θ'_{max}	Maximum tibia rotation velocity	Maximum angular velocity about the longitudinal axis of the shank segment
$My_{ankle,max}$	Maximum ankle inversion moment	Maximum moment about the long axis of the foot
$My_{knee,max}$	Maximum knee abduction moment	Maximum moment about the abduction/adduction axis of the knee joint
$Mx_{knee,max}$	Maximum knee external rotation moment	Maximum moment about the rotation axis of the knee joint
$t_{My\text{ankle,max}}$	Time of maximum ankle inversion moment	Time of occurrence of the maximum ankle inversion moment
$t_{My\text{knee,max}}$	Time of maximum knee abduction moment	Time of occurrence of the maximum knee abduction moment
$t_{Mx\text{knee,max}}$	Time of maximum knee external rotation moment	Time of occurrence of the maximum knee external rotation moment
Fz_{impact}	Vertical impact peak	Impact peak of the vertical ground reaction force
Fz_{active}	Vertical active peak	Active peak of the vertical ground reaction force
Gz_{max}	Maximum loading rate	Maximum loading rate of the vertical ground reaction force

reconstructed using Expert Vision Three-Dimensional Analysis software (Motion Analysis Corporation, Santa Rosa CA, USA). Ground reaction forces were measured using a force plate (2400 Hz; Kistler AG, Winterthur, Switzerland) that was placed in the center of the runway level with the ground. Kinematic and kinetic data was filtered using a zero-lag quadratic low-pass Butterworth filter with a cut-off frequency of 12 and 50 Hz, respectively. Three-dimensional lower extremity kinematics and kinetics were calculated using KinTrak software (The University of Calgary, Calgary, Canada), latter using an inverse dynamics approach. The angle, force and moment curves were normalized to touch-down and toe-off resulting in 101 data points per curve per trial. Extreme point values were determined from these curves (Table 3) and averaged for each condition, session, and subject.

2.5. Statistical analysis

Significant differences between the four insert conditions for all variables were detected using repeated measures analysis of variance (ANOVA) and repeated measures student *t*-tests with the significance level set at 5%.

3. Results

Average curves for lower extremity kinematic and kinetic variables for one representative subject are shown in Fig. 2. In general, the orthotic conditions did affect lower extremity kinematic and kinetic variables (Table 4). Post-hoc statistical power analysis revealed a power greater than 80% for all tests with $P < 0.010$. Data for subject 1 was excluded due to technical errors in the analog data.

3.1. Posting

Posting significantly reduced maximum foot eversion, maximum foot eversion velocity, foot inversion velocity, maximum tibia rotation, and maximum tibia rotation velocity. When using posting, the maximum inversion moment at the ankle joint was reduced, the maximum external rotation moment at the knee joint was increased and the maximum abduction moment at the knee joint occurred significantly later during stance. Posting increased both vertical impact peak and maximum vertical loading rate.

3.2. Molding

Molding significantly increased maximum foot inversion and inversion velocity and reduced maximum tibia rotation. Wearing molded orthotics reduced maximum inversion moment at the ankle joint, increased maximum external rotation moment at the knee joint and delayed both maximum abduction moment and maximum external rotation moment at the knee joint. Vertical impact peak and maximum vertical loading rate were reduced by the molded orthotics.

3.3. Posting and molding

The combination of posting and molding had the same effects as the molding alone. However, maximum inversion moment at the ankle joint, vertical impact peak and maximum loading rate were further reduced and the maximum abduction moment at the knee joint occurred significantly later compared to the molded orthotics.

The effects of molding and posting and molding on lower extremity kinematic and kinetic variables were very similar for each individual (Figs. 3 and 4). Posting had similar effects on maximum foot eversion, maximum foot eversion velocity and maximum inversion moment at the ankle joint across subjects. All subjects were also affected similarly by molding and posting and molding for maximum vertical loading rate and time to maximum abduction moment at the knee joint.

4. Discussion

In general, the kinematic and kinetic variables found in this study showed similar patterns to those reported in previous studies (Stacoff et al., 2000; McClay and Manal, 1999; Bellchamber and van den Bogert, 2000). It has previously been shown that the within-day repeatability of kinematic and kinetic data is very high and that between-day variability can be substantially improved by removing the mean of each day (Kadaba et al., 1989). The convincing statistical results of the current study are in part due to the experimental design, where data for the orthotic conditions were compared to data for a control condition within each session. Thus, most of the between-session variability potentially caused for instance by differences in calibration could be eliminated.

4.1. Posting

The effects of posting on most kinematic variables were significant and consistent across subjects (Figs. 3 and 4). Intuitively, a medial post places the foot in a more inverted position during the stance phase of locomotion. However, these effects seem to be only present during the first half of stance phase as maximum foot eversion was significantly reduced but posting did not affect maximum foot inversion, which occured during the second half of stance phase (Fig. 2a). These small effects of posting on foot inversion may be due to

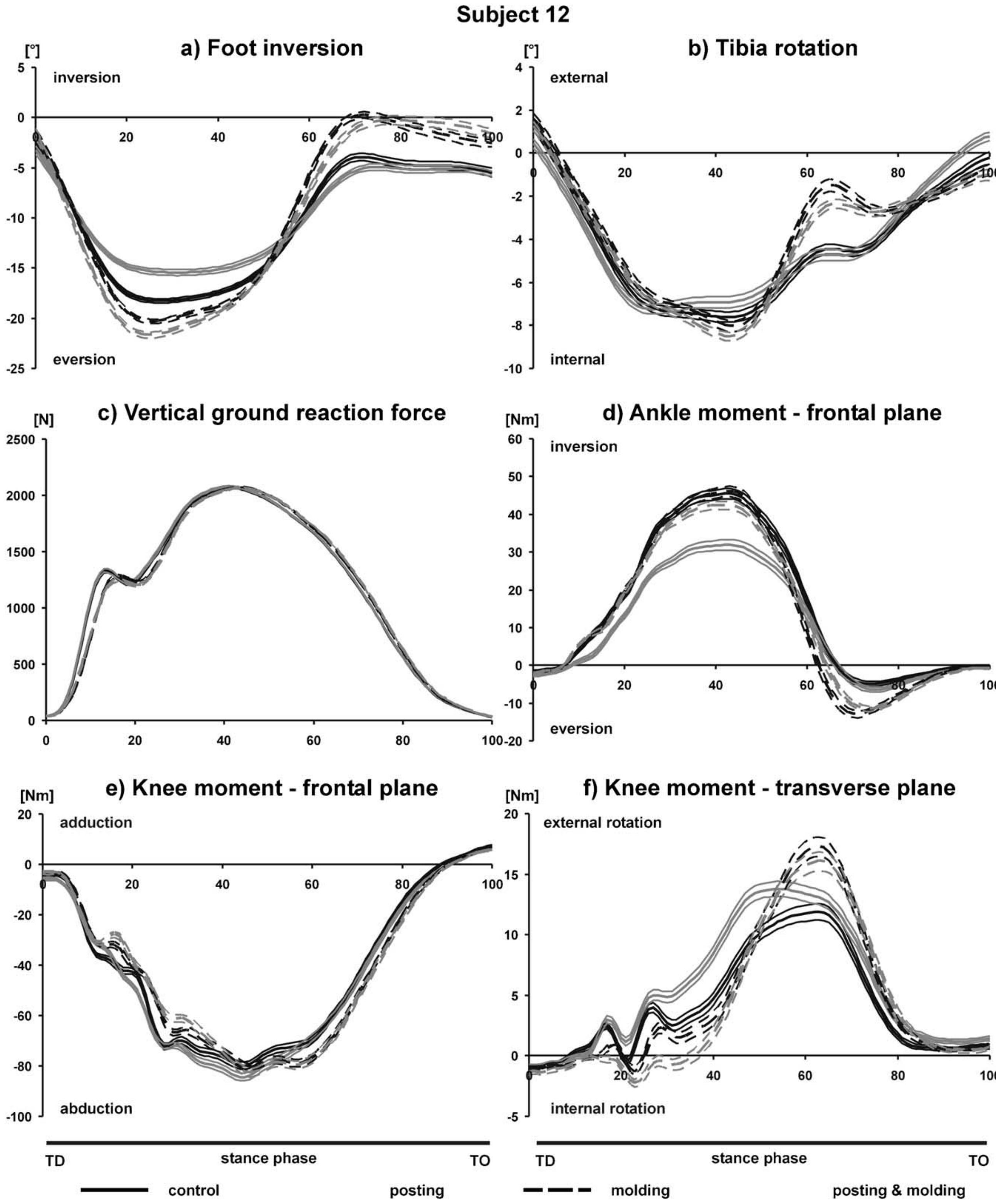

Fig. 2. Average curves (and SE) for kinematic and kinetic variables for subject 12 ($n = 108$ per condition): TD, touch-down; TO, toe-off.

the fact that in the forefoot region the posting orthotics are in contact only with the metarsophalangeal joints and thereby provide relatively little support. It has been previously shown that foot eversion is coupled with internal tibia rotation (Inman, 1976). Indeed, posting also reduced maximal tibia rotation. However, tibia rotation was less affected than foot eversion movement. In general, posting reduced maximum foot eversion and tibia

Table 4
Average values (SE of 20 subjects) of all trials for all kinematic and kinetic variables ($n = 20$ subjects × 9 sessions × 12 trials per condition)

Variable (unit)	Condition								
	Control	Posting		Molding		Posting and molding			
	Average (SD)	Average (SD)	*P*-value control	Average (SD)	*P*-value control	Average (SD)	*P*-value control	*P*-value posting	*P*-value molding
$\beta_{\mathrm{ev,max}}$ (°)	16.0 (2.3)	**13.7 (2.7)**	**<0.001**	16.6 (2.5)	**0.141**	16.9 (3.6)	0.217	**<0.001**	0.434
$\beta_{\mathrm{inv,max}}$ (°)	−0.3 (5.7)	−0.1 (5.6)	0.206	**1.2 (5.9)**	**<0.001**	**1.6 (6.2)**	**0.001**	**0.006**	0.188
θ_{max} (°)	6.0 (4.0)	**5.5 (4.1)**	**0.007**	**5.4 (3.9)**	**0.005**	**5.5 (4.2)**	**0.035**	0.86 1	0.307
$\beta'_{\mathrm{ev,max}}$ (°/s)	464.7 (155.2)	**392.9 (135.0)**	**<0.001**	476.8 (145.0)	0.311	484.4 (141.1)	0.232	**<0.001**	0.487
$\beta'_{\mathrm{inv,max}}$ (°/s)	264.6 (97.7)	**236.7 (91.8)**	**<0.001**	**293.8 (92.1)**	**0.004**	**291.3 (80.3)**	**0.005**	**<0.001**	0.681
θ'_{max} (°/s)	184.9 (52.0)	**176.0 (58.9)**	**0.018**	178.6 (43.3)	0.191	179.5 (44.7)	0.252	0.522	0.749
$My_{\mathrm{ankle,max}}$ (Nm)	30.8 (8.2)	**24.8 (7.4)**	**<0.001**	**28.1 (8.8)**	**0.002**	**26.0 (8.7)**	**0.001**	0.365	**0.002**
$My_{\mathrm{knee,max}}$ (Nm)	62.3 (20.1)	63.0 (22.0)	0.476	62.6 (19.7)	0.751	62.9 (19.2)	0.695	0.895	0.735
$Mx_{\mathrm{knee,max}}$ (Nm)	11.9 (4.0)	**13.4 (5.0)**	**0.001**	**13.3 (4.0)**	**0.006**	**13.7 (4.2)**	**0.006**	0.648	0.153
$t_{My\mathrm{ankle,max}}$ (%)	41.0 (5.5)	41.4 (6.7)	0.539	40.2 (5.5)	0.129	39.9 (6.5)	0.167	0.207	0.694
$t_{My\mathrm{knee,max}}$ (%)	37.5 (11.7)	**39.9 (10.7)**	**0.002**	**43.7 (11.0)**	**<0.001**	**46.3 (9.2)**	**<0.001**	**<0.001**	**0.002**
$t_{Mx\mathrm{knee},max}$ (%)	53.5 (9.7)	54.7 (7.9)	0.237	**57.9 (6.2)**	**<0.001**	**58.9 (5.4)**	**<0.001**	**<0.001**	0.087
Fz_{impact} (N)	1499.1 (255.6)	**1519.4 (265.9)**	**0.026**	**1400.4 (242.5)**	**<0.001**	**1352.3 (233.6)**	**<0.001**	**<0.001**	**<0.001**
Fz_{active} (N)	1674.8 (205.6)	1671.4 (208.3)	0.141	1671.9 (204.1)	0.282	1670.1 (201.6)	0.140	0.725	0.410
Gz_{max} (N/s)	52.5 (11.1)	**53.5 (11.9)**	**0.026**	**44.8 (11.1)**	**<0.001**	**42.0 (10.9)**	**<0.001**	**<0.001**	**<0.001**

P-values of the statistical tests for differences between the orthotic conditions and the control condition and between posting and molding and posting and molding are given. Significant results are printed in bold ($P < 0.05$); post-hoc power >80% for all results with $P < 0.010$.

rotation with the timing of the maxima remaining unaffected, which was reflected in lower maximum foot eversion and tibia rotation velocities, respectively. The less everted maximum foot position with posting resulted in a shorter distance between the ground reaction force and the ankle joint center and led to a reduction in maximum inversion moment at the ankle joint. During most of the stance phase in running the ground reaction force passes laterally to the ankle joint and medially to the knee joint. As the ground reaction force moved closer to the ankle joint center its distance to the knee joint center increased, which contributed to the increase in maximum external rotation moment at the knee joint.

4.2. Molding

Molding had very little effect on foot movement in the frontal plane during early stance phase (Fig. 2a; Table 4). However, molding did significantly reduce maximum tibia rotation. Contrary to the effects of posting, individual results suggest that the effects of molding on maximum foot eversion were not directly coupled to the effects on maximum tibia rotation (Fig. 3). The fact that both maximum foot inversion and maximum foot inversion velocity were significantly reduced with the molding condition suggests that molding of foot orthotics does play a significant role during late stance phase with respect to kinematics. Since molding of foot orthotics has been shown to relieve pain and injuries (Eggold, 1981; Dugan and D'Ambrosia, 1986; D'Ambrosia, 1985; Kilmartin and Wallace, 1994), it should be determined whether these improvements are related to changes in lower extremity kinematics during early stance phase as typically assumed (Eng and Pierrynowski, 1994; Nawoczenski et al., 1995; Smith et al., 1986; Novick and Kelley, 1990; Baitch et al., 1991; Stacoff et al., 2000) or rather to changes in lower extremity kinematics during late stance phase. In comparison to the effects on kinematics, molding did reduce both the magnitude of the vertical impact peak and the vertical loading rate during early stance phase and did not affect the magnitude of the active vertical ground reaction force. It is speculated that molding of foot orthotics increased the amount of shock absorption by providing a larger contact area between foot and foot orthotics as suggested by Redmond et al. (2000) and allowing for necessary foot eversion movement as suggested by Perry and Lafortune (1995). In comparison to the posting condition, both molded conditions are in contact with the foot in the entire forefoot and midfoot regions thereby supporting the medial aspect of the foot and placing the foot in a more inverted position during the second half of stance phase. The more inverted position of the foot resulted in a greater distance between the ground reaction force and the knee joint center with the magnitude of the ground reaction force remaining unaffected, which led to an increase in maximum external rotation moment at the knee joint during this period of stance phase (Figs. 2f and 3). If increased knee joint moments are related to knee injuries such as Patello Femoral Pain Syndrome as suggested by Stefanyshyn et al. (1999), then molding may not be the optimal solution for this particular group of subjects.

4.3. Posting and molding

In the current study, the effects of posting were opposite in direction to the effects of molding for most

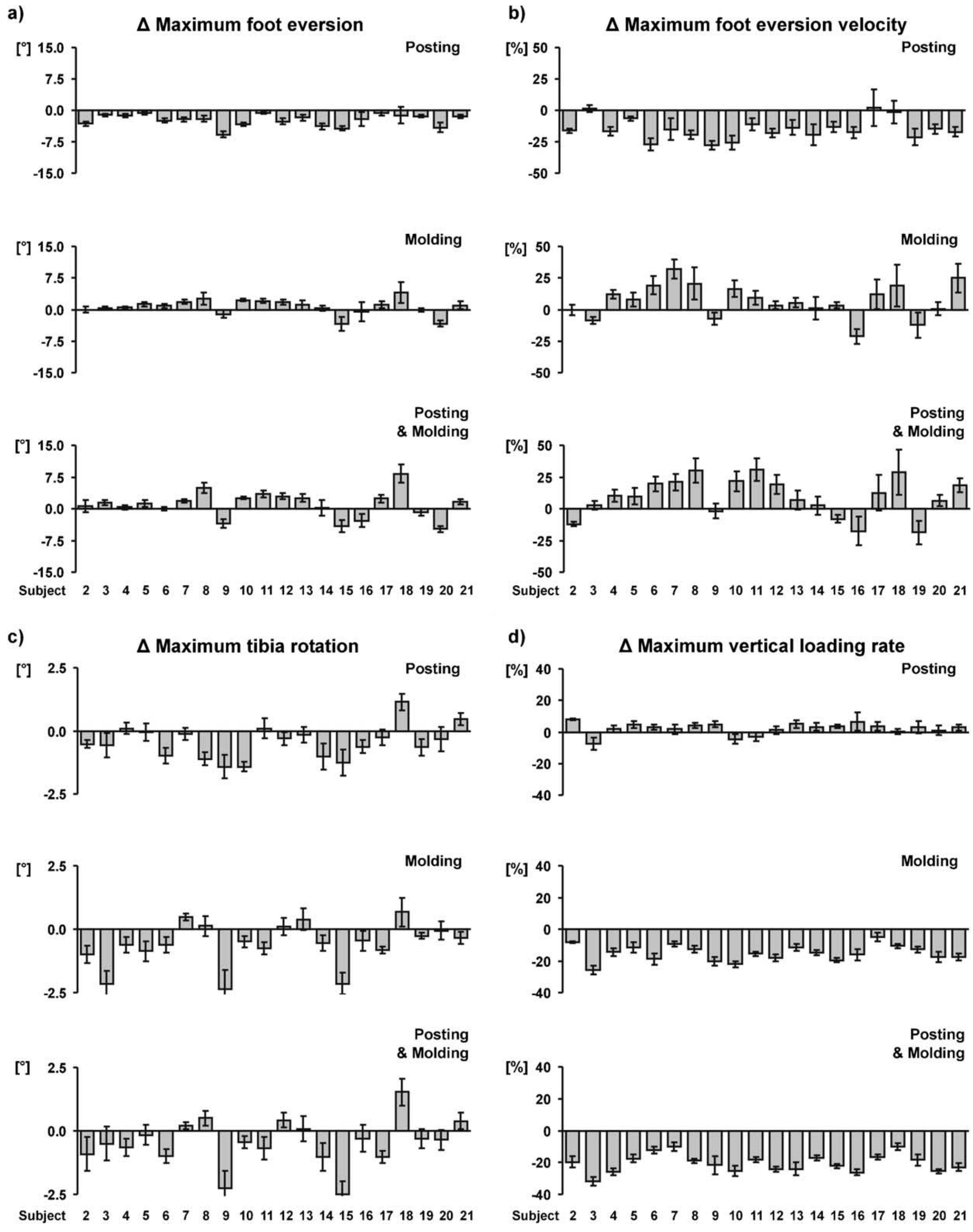

Fig. 3. Average differences (and SE of nine sessions) in ankle joint kinematics and vertical loading rate between the orthotics conditions and the control condition for each subject ($n = 9$ sessions × 12 trials per subject and condition). Differences are given as percent differences where appropriate. Positive bars indicate increases and negative bars reductions.

variables. However, the effects of molding and posting combined were very similar to molding (Figs. 3 and 4; Table 4). One might expect the effects of posting and molding to be a combination of the individual effects of posting and molding, which was not observed in the current data set. However, extrinsic posting modifications have been developed to increase the ability of foot orthotics to resist abnormal forces acting upon the

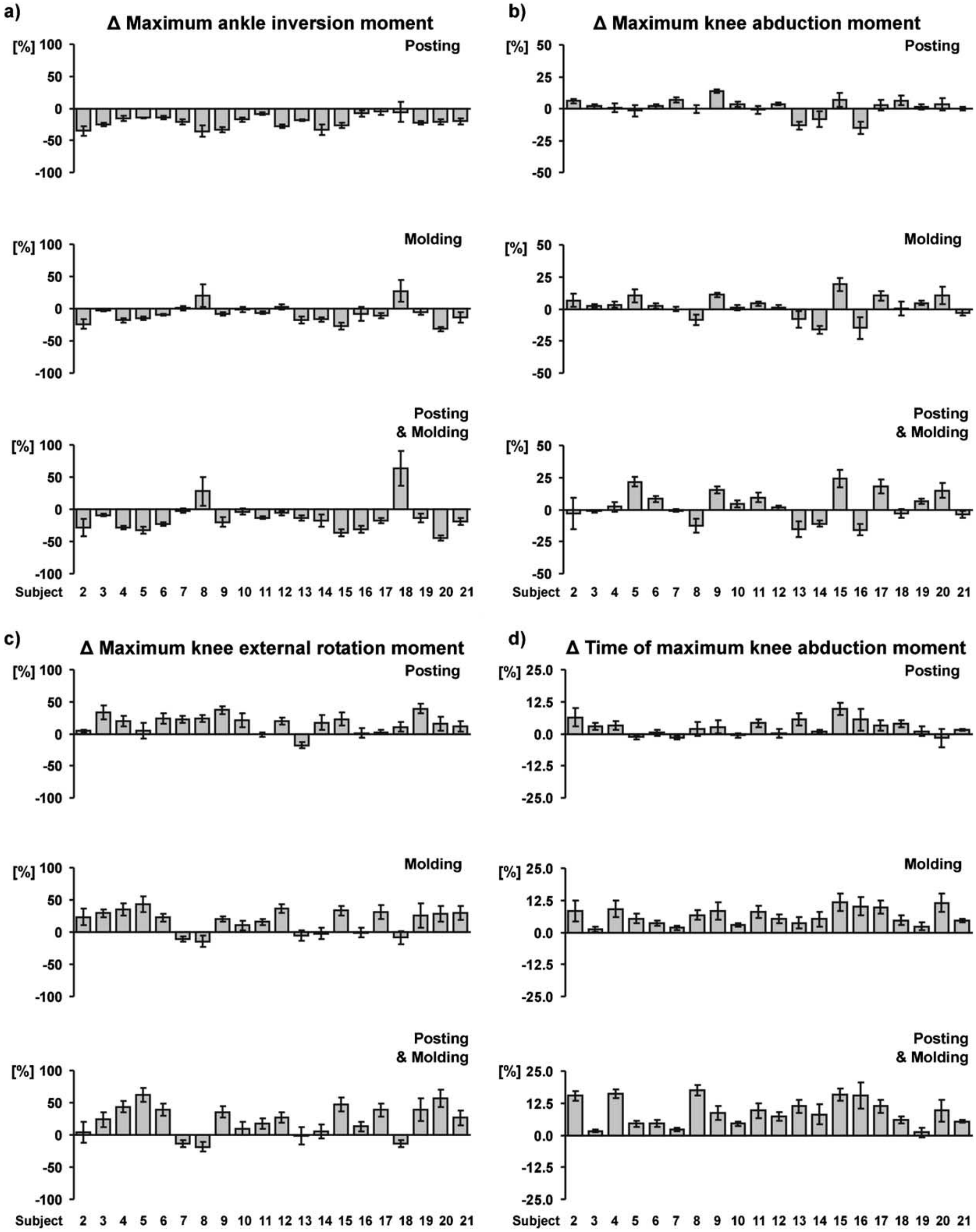

Fig. 4. Average differences (and SE of nine sessions) in ankle and knee joint moments between the orthotics conditions and the control condition for each subject ($n = 9$ sessions $\times$ 12 trials per subject and condition). Differences are given as percent differences where appropriate. Positive bars indicate increases and negative bars reductions.

rearfoot (Root, 1994). Indeed, the results of the current study support this speculation as the effects of molding and posting on kinematic and kinetic variables were more prominent than the effects of molding alone. Thus, the results of this study suggest that molding overrides the effects of posting and that the effects of molding can be increased by combining it with posting.

In conclusion, posting and molding of foot orthotics did affect lower extremity kinematics and kinetics. The effects of isolated posting and isolated molding were different and when combining posting and molding, the effects of molding were dominant. If increased maximum foot eversion is in fact a risk factor for running injuries as suggested by Messier and Pittala (1988), then posting may be used to relieve or prevent such injuries. On the other hand, if increased vertical loading rate proves to be related to injuries as indicated by Hreliac et al. (2000), molded foot orthotics may provide a better solution for runners prone to injuries. The results of this study showed that the effects of foot orthotics on maximum foot eversion and vertical loading rate are conflicting, which is in agreement with earlier findings (Perry and Lafortune, 1995). Therefore, it remains to be determined with epidemiological studies whether posting or molding is more beneficial with respect to overuse running injuries.

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