The effect of material characteristics of shoe soles on muscle activation and energy aspects during running

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Abstract

The purposes of this study were (a) to determine group and individual differences in oxygen consumption during heel–toe running and (b) to quantify the differences in EMG activity for selected muscle groups of the lower extremities when running in shoes with different mechanical heel characteristics. Twenty male runners performed heel–toe running using two shoe conditions, one with a mainly elastic and a visco-elastic heel. Oxygen consumption was quantified during steady state runs of 6 min duration, running slightly above the aerobic threshold providing four pairs of oxygen consumption results for comparison. Muscle activity was quantified using bipolar surface EMG measurements from the tibialis anterior, medial gastrocnemius, vastus medialis and the hamstrings muscle groups. EMG data were sampled for 5 s every minute for the 6 min providing 30 trials. EMG data were compared for the different conditions using an ANOVA ($\alpha = 0.05$). The findings of this study showed that changes in the heel material characteristics of running shoes were associated with (a) subject specific changes in oxygen consumption and (b) subject and muscle specific changes in the intensities of muscle activation before heel strike in the lower extremities. It is suggested that further study of these phenomena will help understand many aspects of human locomotion, including work, performance, fatigue and possible injuries.

1. Introduction

Heel–toe runners experience impact forces between 1.0 and 2.5 times body weight. One would expect impact forces to produce substantial vibrations of the soft tissue packages of the lower extremities (e.g. quadriceps, hamstrings, triceps surae). However, impact related soft tissue vibrations are small or not apparent. Thus, the soft tissue packages must have mechanical characteristics that correspond to heavily or critically damped mechanical systems. Since vibrations are small for any shoe-surface combination the mechanical characteristics of the soft tissues must be adjusted by muscle pre-activation (Nigg, 1997; Wakeling and Nigg, 2001) and one should expect muscle and subject specific reactions for different shoe conditions.

Thus, one may speculate that muscles are programmed to avoid vibrations (Nigg, 1997). A specific muscle group should change its activity when the frequency of the input signal is close to its natural frequency and the changes in activity should depend on the mass of the soft tissue package and its mechanical characteristics. Furthermore, it is speculated that any change in muscle activity affects work and performance of the human locomotor system (Nigg, 2000). Thus, effects on muscle activity should be observable by studying EMG signals and effects on work by studying oxygen consumption. However, experimental evidence for such phenomena is not available.

The purposes of this study were:

(a) to determine group and individual differences in oxygen consumption during heel–toe running and
(b) to quantify the differences in EMG activity for selected muscle groups of the lower extremities.

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When running in shoes with different mechanical heel characteristics.

Specifically the following hypotheses were tested:

H1 The group differences in oxygen consumption between the elastic and the viscous shoe condition are small and not significant.

H2 There are groups of subjects with significantly less, equal and more oxygen consumption when running in shoes with elastic and viscous heels.

H3 Changes in shoe conditions change EMG activity of selected lower extremity muscles. The differences are muscle and subject specific.

2. Methods

Twenty proficient male *runners* participated in this study and gave written informed consent. They were free of any serious injuries at the time of study.

Two *shoe conditions* were used in this study. The two shoes were identical (same uppers, outsoles, insoles, etc.) but differed in the midsole materials of the heel. One heel material was of medium hardness (shore $C = 45$) and mainly elastic. The other heel material was softer (shore $C = 26$) and more viscous. To quantify the differences between the materials the heels of the two shoes were tested in a testing machine (MTS Systems Corporation, Eden Prairie, Minnesota, USA). A heel-shaped indenter attached to the actuator of the MTS machine was used to compress the heel of each shoe at a speed of 300 mm/s. The tests were performed to approximately 14 mm deformation to simulate actual deformation during locomotion. Three trials were performed on each shoe. The results of these tests are illustrated in Fig. 1.

The two shoes differed in hardness (as measured with a durometer) and in visco-elasticity (as indicated by the

remaining deformation after the task). One shoe (solid line) was harder and more visco-elastic. The other shoe (dotted line) was softer and less visco-elastic. Shoe A will be named *viscous,* shoe B will be named *elastic* in the text. The mass of the shoes differed by less than 6 g with the elastic shoe (size 9) having a mass of 293 g and the visco-elastic shoe (size 9) having a mass of 288 g. All runners used at the time of the experiment size 9 or 10 (US) running shoes.

Oxygen consumption was quantified while running on a portable treadmill (Quinton: Q65, Seattle, Washington) in three testing sessions (Williams, 1985; Morgan and Craib, 1992; Martin et al., 1993) conducted at a similar time of day for each subject to eliminate the potential variation in VO_2 due to circadium rhythm. First, a *calibration session* was used to determine aerobic threshold, anaerobic threshold and VO_{2max}. Two *testing sessions* were used to quantify the oxygen consumption for the two shoe conditions. The two *testing sessions* started with a 10–15 min warm-up period. The actual test consisted of steady-state runs of 6 min duration, running slightly above the aerobic threshold. The four VO_2 values measured every 30 s for the final 2 min were used to determine the mean oxygen consumption for a given shoe and test. A 3-min rest period was allowed between each run. One testing session had a testing sequence of v–e followed by e–v. The other testing session had the testing sequence e–v followed by v–e (where e and v corresponded to the "elastic" and the "viscous" shoe condition). The sequence used in the first test session was randomly assigned. This procedure provided 4 pairs of oxygen consumption results for comparison.

Individual oxygen consumption results were defined as different for the two shoe conditions when the VO_2 values for all four paired comparisons (v–e, e–v, e–v, v–e) were consistently higher or lower for one shoe condition compared to the other shoe condition. Based on the oxygen consumption results, three groups were defined:

Viscous group: VO_2(elastic) > VO_2(viscous) for all four comparisons.
Elastic group: VO_2(elastic) < VO_2(viscous) for all four comparisons.
Neutral group: VO_2(elastic) ≈ VO_2(viscous) for not consistent comparisons.

A paired *T*-test was performed to compare between the two shoe conditions ($\alpha = 0.05$) for the whole group.

Muscle activity was quantified for the right leg from EMG (1200 Hz, Biovision, Germany) measured in a special testing session on the same treadmill. Oxygen consumption measurements and EMG measurements were not made simultaneously because simultaneous measurements could influence each other negatively. Bipolar surface EMG measurements were taken from for the tibialis anterior, medial gastrocnemius, vastus
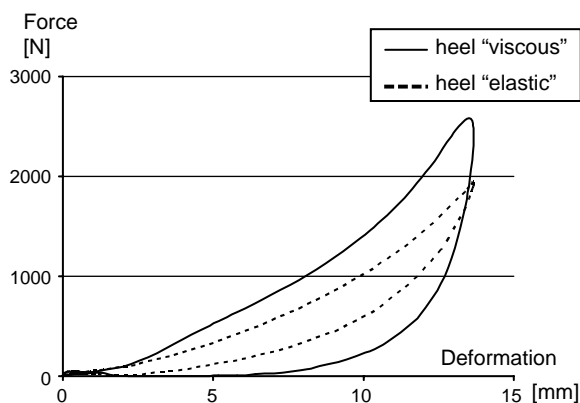

Fig. 1. Force–deformation diagrams for the two heels of the tested shoes as determined through MTS testing at 300 mm/s. Each curve is the average of three test results under the same conditions.

medialis and the hamstrings group. Vertical force data from the back right support leg of the treadmill (Kistler AG, Winterthur, Switzerland, 1200 Hz) were used to determine the time of the right foot contact. EMG data were sampled for 5 s every minute for the 6 min. A total of 5 steps per data collection were analyzed providing 30 trials (steps) for analysis. EMG data were filtered (von Tscharner, 1999) with a Bandpass Filter (20–400 Hz cut-off). A root mean square (RMS) calculation was performed on the filtered EMG data from 50 ms prior to contact to the time of first contact with the treadmill (muscle pre-activation). The top and bottom 10% of the RMS data were removed in order to eliminate possible outliers. Therefore, results from 24 foot-contacts were used in the analysis for each shoe condition and subject. This data were compared for the different conditions using an ANOVA ($\alpha = 0.05$).

The results for subject 13 were excluded from further analysis because the oxygen consumption difference between the 2 days was more than 10%. The results for subject 15 were excluded because the subject did not complete the oxygen consumption measurements. For the remaining 18 subjects, EMG data were excluded for the vastus medialis muscle for four subjects (no. 4, 7, 10 and 14) because there was too much noise in the signal that could not be filtered out.

3. Results

The results are grouped with respect to the following aspects, (a) description of a typical EMG data set for treadmill running, (b) group results and (c) individual results for oxygen consumption and EMG data.

3.1. EMG-force data set

A data set for one ground contact for the four muscles involved is illustrated in Fig. 2 for subject #20.

3.2. Group differences for the two shoe conditions

For *oxygen consumption*, the mean group differences between the elastic and the viscous shoe condition were small and not significant for both days of testing [Day 1: VO_2(elastic) $= 38.9 \pm 4.3$ ml/kg/min,
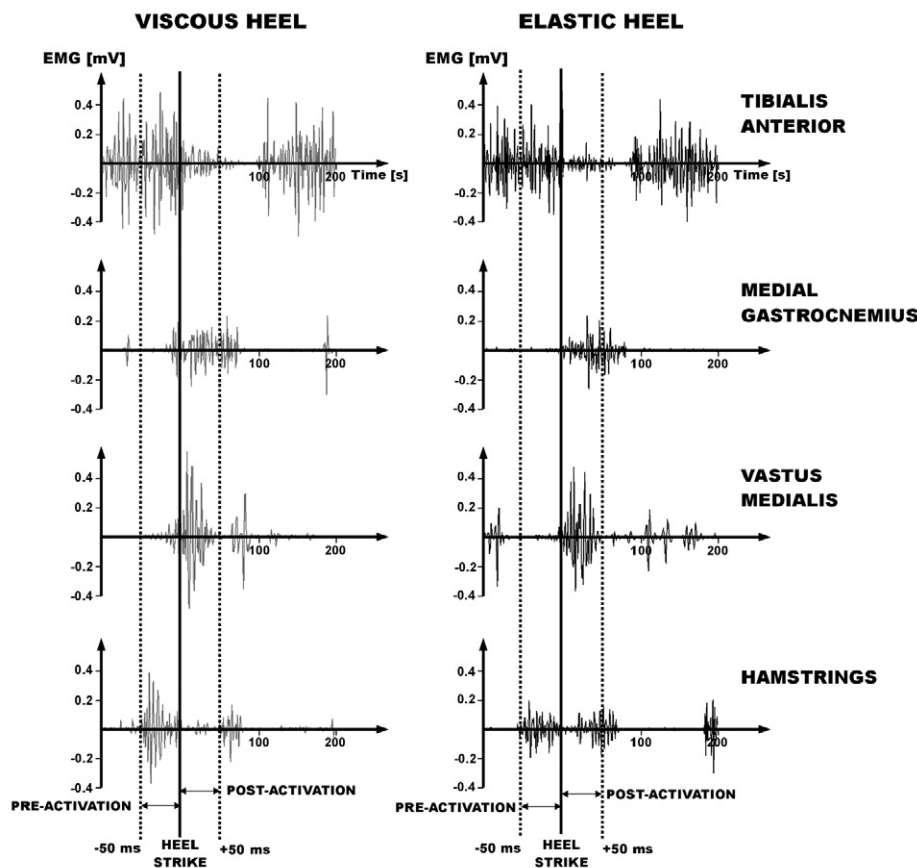

Fig. 2. Illustration of the EMG signals for the four muscles tibialis anterior, gastrocnemius medialis, vastus medialis and hamstrings for one subject (subject 20) while running with the shoe with the viscous (left) and the elastic (right) heel. The solid vertical line indicates first ground contact, the dotted lines indicate 50 ms before and 50 ms after first ground contact.
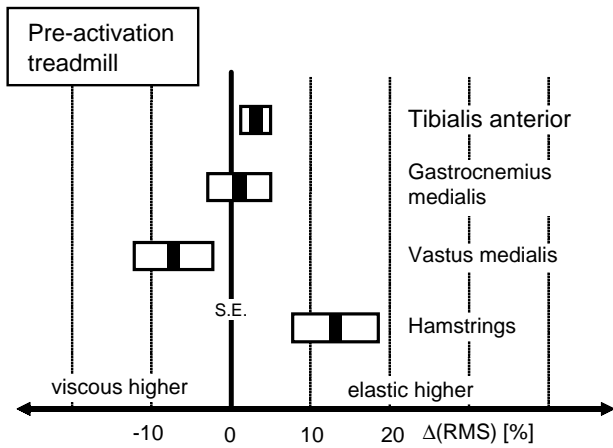
Fig. 3. Percentage changes of the mean RMS values with SE for the four muscles for the 18 subjects. A positive sign indicates that the RMS was higher for the elastic than for the viscous shoe condition.

VO_2(viscous) $= 38.9 \pm 4.5$ ml/kg/min; Day 2: VO_2(elastic) $= 39.4 \pm 3.4$ ml/kg/min, VO_2(viscous) $= 39.4 \pm 3.7$ ml/kg/min]. Thus, hypothesis H1 was supported by the results of this study.

The RMS of the *EMG measurements* for the four muscles measured showed no significant group differences between the two shoe conditions (Fig. 3). The relative differences in the pre-activation between the averages for the elastic and viscous shoe conditions were 3.2% for the tibialis anterior, 0.9% for the gastrocnemius, −7.2% for the vastus medialis and 13.2% for the hamstrings.

4. Individual results

The individual differences in *oxygen consumption* are illustrated in Fig. 4. Five subjects (2, 3, 8, 18 and 19) used in all four comparisons less oxygen for the elastic shoe–heel situation. Five subjects (4, 6, 7, 16 and 20) used in all four comparisons less oxygen for the viscous shoe heel situation. Eight subjects (1, 5, 9, 10, 11, 12, 14 and 17) had not consistent results for the four comparisons. Thus, hypothesis H2 was supported by the results of this study.

The RMS of the EMG showed muscle and subject specific results. Thus, hypothesis H3 was supported. The RMS of the EMG pre-activation showed some systematic changes for the vastus medialis muscle (Fig. 5). All five subjects in the "elastic" group, the group that used more oxygen in the visco-elastic shoe, showed a higher vastus medialis pre-activation for the viscous shoe condition. The average difference in the RMS for this muscle was 20.3% with a range between 3.5% and 65.7%. All three subjects in the "viscous" group for which EMG results were available (6, 16 and 20) showed a higher vastus medialis pre-activation for the elastic
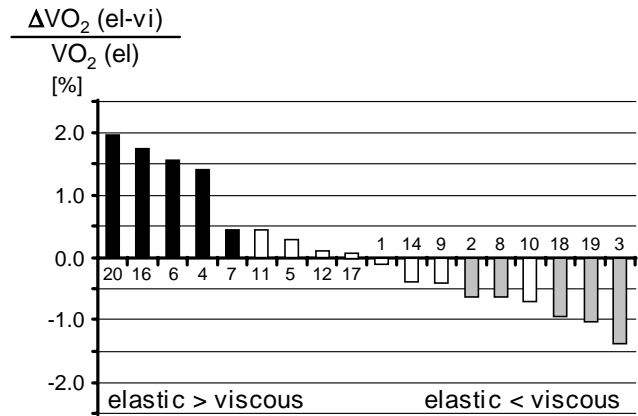

Fig. 4. Individual normalized differences in oxygen consumption between the elastic and the viscous shoe condition. Positive values indicate that VO_2(elastic) > VO_2(viscous). Negative values indicate that VO_2(elastic) < VO_2(viscous). The differences were determined based on four oxygen measurements during four different trials per shoe condition (a total of 16 measurements per shoe and 32 measurements per difference). The shaded bars indicate the five subjects that had the same positive difference between the elastic and the viscous shoe condition for both days.
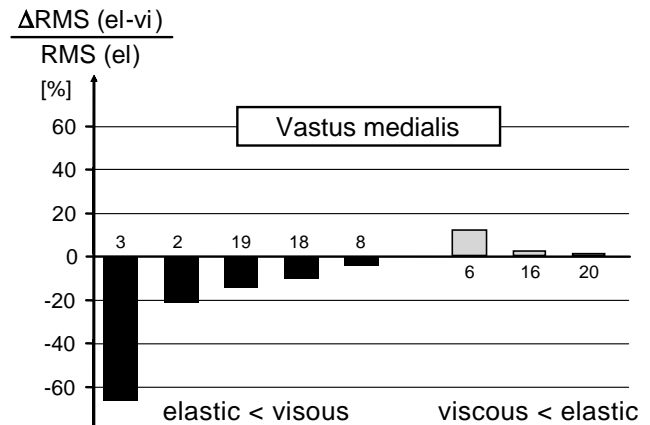

Fig. 5. Relative difference of the EMG-RMS [(elastic–viscous):(elastic)] for the vastus medialis muscle for the elastic (black) and the viscous group (gray). The viscous group has only three results since the EMG data for the other two members of this group were rejected.

shoe condition. The average difference in the RMS for this muscle was 4.7% with a range between 0.9% and 11.7%. The other muscles did not show a systematic difference.

5. Discussion

The purposes of the study were to determine group and individual differences in oxygen consumption during heel–toe running in shoes with elastic or visco-elastic heel materials and to investigate whether

observed differences would be associated with changes in muscle activity.

5.1. Oxygen consumption

The results of this study confirmed that oxygen consumption did, in the average, not differ between the two shoe conditions. However, individual subjects showed systematic and consistent differences of up to 2% (Fig. 4) in oxygen consumption for the two tested shoe heel materials. The finding that runners use less oxygen when running with visco-elastic heel material is counterintuitive and is generally not expected. However, the experimental results for the group that used less oxygen with the visco-elastic heels (the "viscous" group) is in line with theoretical predictions made earlier that viscous shoes sole material may, under certain conditions, require less work for a given locomotion task (Nigg and Anton, 1995).

Thus, the often-used statement that elastic shoe midsole materials are more advantageous for performance than visco-elastic materials is not correct. Some subjects performed better when using visco-elastic and others when using elastic heel midsole materials. Taking into account that the shoes used in this study were arbitrarily selected (the only goal was to have one shoe with an elastic and one with a visco-elastic heel) and that the selected visco-elastic materials were determined by availability, one could speculate that differences in oxygen consumption may even be higher if the shoe sole material was optimally tuned to each subject. However, the criteria for *optimal tuning* are not known yet.

5.2. Muscle activity

Changes in muscle activity can occur with respect to timing, intensity and frequency. There were no changes in timing registered for the two shoe conditions. The changes in the intensity of the muscle activity (RMS) before heel strike when changing footwear were in some cases quite substantial (Fig. 5). The muscle "package" with the smallest mass had the lowest range of change of RMS (TA: 35%), the larger muscle "packages" had a range of changes in muscle activity between 85% and 91% (GM: 91%; VM: 90%; HA: 85%) indicating that larger muscle activity changes were needed for the soft tissue packages with the bigger masses.

The intensity of the EMG pre-activation showed some systematic changes for the vastus medialis muscle (Fig. 6). All five subjects in the "elastic" group, the group that used more oxygen in the visco-elastic shoe, showed a higher vastus medialis pre-activation for the visco-elastic shoe condition. The average difference in the RMS for this muscle was 20.3% with a range between 3.5% and 65.7%. All three
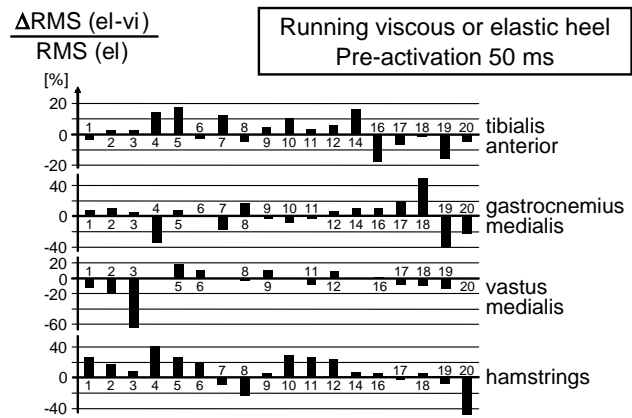

Fig. 6. Relative EMG RMS between the elastic and the viscous shoe condition for the vastus medialis muscle for two groups of subjects, subjects that used less oxygen in the elastic shoe condition (left) and subjects that used less oxygen in the viscous shoe condition (right).

subjects in the "viscous" group (6, 16 and 20) showed a higher vastus medialis pre-activation for the elastic shoe condition. The average difference in the RMS for this muscle was 4.7% with a range between 0.9% and 11.7%. The other muscles did not show a systematic difference.

Changes in the mean wavelet frequencies between shoe conditions were not significant for the group comparisons. However, in analogy to the individual RMS data, there were substantial subject and muscle specific changes in the mean frequencies for the different shoe conditions.

The EMG signals before heel strike had a significant and substantially higher mean wavelet frequency than the signals after heel strike confirming previous experimental results (Wakeling et al., 2001). The frequency characteristics of the EMG signals are influenced by the conduction velocity and the shape of the action potential (Lindström et al., 1970; Stulen and de Luca, 1981; Solomonow et al., 1990). Differences in conduction velocities may be attributed to fast and slow twitch fibers. However, experimental evidence for this functional relationship is contradictory (Karlson, 1999; Wakeling et al., 2002). The experimental results of this study suggest that EMG activities before and after heel strike belong to two different events. If is speculated that the EMG activities before heel strike are preprogrammed based on the expected impact shock and are related to a "muscle tuning" activity (Nigg and Wakeling, 2001) while the EMG activities after heel strike belong to a reflex arc event.

If one accepts the speculation that changes in EMG wavelet frequencies are related to changes in muscle fiber recruitment, one may suggest that "muscle tuning" uses more fast twitch muscle fibers and the "muscle tuning" be related to fatigue. Thus, it should be studied,

whether a reduction of muscle activity before heel strike is associated with fatigue and/or performance.

5.3. Signal frequencies

During running and many other human locomotion activities various frequencies are rather close. The mean frequency of the impact force signal during heel strike is between 5 and 20 Hz. When running on a treadmill this treadmill has a natural frequency about 10–20 Hz. The soft tissue packages (e.g. triceps surae, hamstrings, etc.) have a natural frequency around 5–60 Hz. Thus, the mean frequencies of impact force signals during heel–toe running are close to the natural frequencies of the soft tissue packages of the lower extremities. Consequently, it seems important to understand strategies that can be applied to avoid resonance phenomena of the soft tissue packages. One strategy consists of using the filtering abilities of shoe soles, sport surfaces and shoe inserts; frequency considerations must be performed to understand the possibilities and the limitations. For some subject in the tested population the viscous for others the elastic heel was the "better" solution with respect to oxygen consumption. Another strategy consists in changing the mechanical characteristics (F and c) of the muscles in the soft tissue packages, moving their natural frequency away from the input frequency of the shock wave. It may be that such changes in input frequencies were responsible for earlier published differences in oxygen consumption with different shoes or surfaces (Bates et al., 1978; Caitlin and Dressendorfer, 1979; Clarke et al., 1983a b; Frederick et al., 1983; Fukuda et al., 1983; Stacoff and Kaelin, 1983; Nigg and Bahlsen, 1988; Hamill et al., 1988; Milani et al., 1995).

5.4. Conclusion

The findings of this study showed that changes in the heel material characteristics of running shoes are associated with (a) subject specific changes in oxygen consumption, (b) subject and muscle specific changes in the intensities of muscle activation before heel strike in the lower extremities and (c) subject and muscle specific changes in the mean wavelet frequencies of the EMG signals. The functional understanding of these changes is in its infancy. However, it is suggested that the further study of these phenomena will help understand many aspects of human locomotion, including work, performance, fatigue and possible injuries.

Acknowledgements

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