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Aging of running shoes and its effect on mechanical and biomechanical variables: implications for runners

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Abstract

This study investigates the effect of running shoes' aging on mechanical and biomechanical parameters as a function of midsole materials (viscous, intermediate, elastic) and ground inclination. To this aim, heel area of the shoe (under calcaneal tuberosity) was first mechanically aged at realistic frequency and impact magnitudes based on a 660 km training plan. Stiffness (ST) and viscosity were then measured on both aged and matching new shoes, and repercussions on biomechanical variables (joint kinematics, muscular pre-activation, vertical ground reaction force and tibial acceleration) were assessed during a leg-extended stepping-down task designed to mimic the characteristics of running impacts. Shoes' aging led to increased ST (means: from 127 to 154 N · mm⁻¹) and decreased energy dissipation (viscosity) (means: from 2.19 to 1.88 J). The effects induced by mechanical changes on body kinematics were very small. However, they led with the elastic shoe to increased vastus lateralis pre-activation, tibial acceleration peak (means: from 4.5 g to 5.2 g) and rate. Among the three shoes tested, the shoe with intermediate midsole foam provided the best compromise between viscosity and elasticity. The optimum balance remains to be found for the design of shoes regarding at once cushioning, durability and injury prevention.

Keywords: footwear, material fatigue, locomotion, running injury

Introduction

Running exposes the human body to repetitive impacts generating shock waves that propagate through the musculoskeletal system up to the head. Combined with anatomical predispositions, such as excessive subtalar pronation, those repetitive loadings can contribute to an increased risk of injury (Shorten, 2000).

Regarding the shoe, cushioning properties mostly depend on the stiffness (ST) of the midsole (Shorten, 2000). For example, high midsole ST has been shown to increase tibial acceleration peak and rate during running (Heidenfelder, Sterzing, & Milani, 2009). A similar increase of tibial acceleration peak with increase of the impact surface ST has been highlighted by Lafortune, Hennig, and Lake (1996) in a human pendulum task. This task allowed full control of kinematics. Participants were lying on a hanged bed with their right knee straight. Their right foot crashed into a wall after a pendulum movement of the bed created by the experimenter. Softer shoes have (Shorten & Mientjes, 2003, 2011) been shown to decrease the loading rate (i.e. the rising slope of the

vertical ground reaction force). The effect of midsole ST however remains controversial as regard to impact peak magnitude during running. Indeed, some studies reported no effect of midsole ST on impact peak magnitude (Clarke & Frederick, 1983; Heidenfelder, Sterzing, & Milani, 2010; Nigg, Bahlsen, Luethi, & Stokes, 1987), while others reported a reduction of this variable with a stiffer shoe (Milani, Hennig, & Lafortune, 1997) or with a shoe having intermediate midsole properties (Shorten & Mientjes, 2003, 2011).

Concerning the human body, it has been shown that passive mechanisms such as heel-pad deformation (Aerts, Ker, De Clercq, Ilsley, & Alexander, 1995; Valiant, 1990) and soft tissues vibrations (Lafortune, Lake, & Wilson, 1994) reduce shock wave magnitude while active mechanisms such as knee flexion (Lafortune et al., 1996; Potthast, Brüggemann, Lundberg, & Arndt, 2010) or calcaneal eversion (Perry & Lafortune, 1995) reduce its propagation. Adjustments of lower limb muscular activity in reaction to impact forces may also reduce soft tissue vibrations (Boyer & Nigg, 2004; Nigg, 2001; Nigg & Liu, 1999; Wakeling, Pascual, & Nigg, 2002).

Ethylene-vinyl acetate foam is a viscoelastic material constituting the midsole of most running shoes. As a result of aging, the air content of the ethylene-vinyl acetate foam decreases. Wrinkles and collapses can be observed in the walls of ethylene-vinyl acetate cells (Mills & Rodriguez-Perez, 2001). This phenomenon subsequently influences the mechanical properties of the midsole that becomes stiffer, thinner and loses its capacity to dissipate energy (Schwanitz & Odenwald, 2008; Verdejo & Mills, 2004a). Runners' biomechanics can in turn be affected as emphasised by several studies. Indeed, the comparison of the effect of new shoes versus shoes fatigued using a finite element model (Even-Tzur, Weisz, Hirsch-Falk, & Gefen, 2006), 500 km of run (Verdejo & Mills, 2004b) or an accelerated aging process (Morio, Gueguen, Baly, Berton, & Barla, 2009), respectively, revealed an increase of stresses on foot heel pad, peak plantar pressure and vertical ground reaction force loading rate and tibial acceleration peaks at heel impact. Kong, Candelaria, and Smith (2009) also reported changes in running kinematics when training 200 miles with the same shoes.

Owing to their biomechanical consequences, deteriorations of shoe cushioning with aging may lead to injuries. Indeed, Taunton et al. (2003) highlighted a correlation between shoe age and injury occurrence in their prospective study on running injuries. Shoe aging would cause an increased ST. This increase of ST will potentially cause the modification of biomechanical parameters as loading rate or tibial acceleration peak. Interestingly, previous study (Milner, Ferber, Pollard, Hamill, & Davis, 2006) associated these two parameters to stress fracture appearance.

Despite the important number of studies focusing on the effect of shoe aging on either mechanical or biomechanical variables, only a few merged a mechanical characterisation of midsole properties during aging with an evaluation of their biomechanical consequences. Moreover, most of the aging processes designed until now were unrealistic in terms of frequency, magnitude and/or rest time of the mechanical loading, thus possibly overestimating "normal" aging. For example, Morio et al. (2009) applied 2 kN impacts at 2.5 Hz for 100 000 continuous cycles, and Schwanitz and Odenwald (2008) applied 240 000 consecutive cycles.

The purpose of this study was thus to investigate the effects of the aging of different running shoes on their mechanical properties and the repercussions on biomechanical responses of the human body at impact. To this aim, we first designed a mechanical aging method based on mechanical loading. We then quantified its effect on three shoes with different midsole materials (elastic, viscous or intermediate). And we finally observed the repercussions on

biomechanical variables by comparing human body responses at impact when wearing the aged shoes versus three new ones. This aging effect was also tested in a situation challenging foot inclination at impact to observe any possible aging–inclination interaction.

From a mechanical point of view, it was hypothesised that aging would induce an increased ST and a decreased capacity to dissipate energy (i.e. one parameter representing viscosity) for all shoes although in a different pattern depending on midsole material. Indeed, Brücker, Odenwald, Schwanitz, Heidenfelder, and Milani (2010) showed, using a mechanical fatigue test machine, that damping parameters evolve differently depending on the material. In locomotion tasks with controlled kinematics, fatigued shoes would thus induce higher impact forces than the new ones, and these variations may be more or less important depending on the material.

Methods

Mechanical aging

The mechanical part of this study was aimed at evaluating the effect of a realistic mechanical aging of the heel area of the shoes on their midsoles' properties. To this aim, we designed a protocol intended to replicate, using a mechanical test machine (Amsler HC5, [®]Zwick Roell, Ulm, Germany), the effects of a regular use of running shoes by rear foot striker trail runners.

A 2-month training plan for trail runners usually comprises approximately 660 km broken down in daily sessions that differ from one another in terms of intensity (expressed as a function of the maximal aerobic speed, MAS), duration and rest time. Based on examples of such training plans, we designed an 8-week plan with 5 sessions per week performed at 65% and/or 100% MAS for a total distance of about 660 km (Table I). For this training plan to be reproduced by a mechanical machine, impact force had to be defined in terms of stride frequencies and vertical ground reaction force profiles. Three participants (mean MAS = 17 km · h⁻¹ = 4.7 m · s⁻¹) were then asked to run at 65% and 100% m along a 30-m runway. The corresponding stride frequencies and vertical ground reaction forces were computed from 3 valid trials (requested speed ± 0.3 m · s⁻¹ controlled by photoelectric sensors) using data from a video camera and a force platform ([®]Kistler 9281 CA operating at 2000 Hz) inserted into the runway.

Mechanical experimentation

The mechanical machine was programmed according to the training plan and used to age 3 athletic running shoe models of the same appearance but

Table I. Description of training plan intended to be reproduced by the Zwick machine to simulate the mechanical aging of shoes.

	Session description	Duration
Standard week 1		
Session 1	30 min (65% MAS) then 10×1 min 30 s (100% MAS – R = 1 min) then 10 min (65% MAS)	1 h 5 min
Session 2	30 min (65% MAS) then $2 \times 10 \times 30$ s–30 s (100% MAS – 65% MAS) then 10 min (65% MAS)	1 h
Session 3	1 h 30 min (65% MAS)	1 h 30 min
Session 4	1 h (65% MAS)	1 h
Session 5	1 h (65% MAS) then 15 min (100% MAS) then 10 min (65% MAS) then 10 min (100% MAS) then 5 min (65% MAS)	1 h 40 min
Standard week 2		
Session 1	30 min (65% MAS) then 10×2 min (100% MAS – R = 1 min) then 10 min (65% MAS)	1 h 15 min
Session 2	20 min (65% MAS) then 1 h (100% MAS) then 5 min (65% MAS)	1 h 25 min
Session 3	1 h 30 min (65% MAS)	1 h 30 min
Session 4	1 h (65% MAS)	1 h
Session 5	1 h 15 min (65% MAS) then 15 min (100% MAS) then 10 min (65% MAS)	1 h 40 min

Notes: Each 5-session standard week was reproduced 4 times. Speeds expressed in maximal aerobic speed (MAS) are presented in brackets. R stands for rest.

For example $10 \times 1' 30''$ (100% – R = 1') represents 10 times 1' 30'' at 100% of MAS and 1 min rest. $10 \times 30'' - 30''$ (100% – 65%) means 10 time 30'' at 100% of MAS and 30'' at 65% of MAS.

with viscous, intermediate or elastic ethylene-vinyl acetate foam as midsole material. Each shoe model (elastic, viscous or intermediate) was produced in two identical samples with same midsole and upper materials. Before the fatiguing protocol, only one model was submitted to the fatiguing protocol while the matching one was characterised, but kept new until the biomechanical protocol.

The mechanical machine reproduced the estimated running impact forces (frequency and magnitude) by vertical compressions (Figure 1) of a circular stamp with convex surface (diameter = 45 mm; radius of curvature = 37.5 mm) on the heel area of the shoes. The mechanical load was applied only on the heel area of the shoe as the characteristics of the fore part of the midsole have no possible influence on biomechanical parameters measured when only the heel contacts the force platform as it is the case in this study.

The effect of the aging protocol on shoes' mechanical characteristics was evaluated by computing their ST and energy loss based on force/displacement measurements performed at the beginning and the end of each aging session. These measures consisted

of 10 compression/relaxation cycles performed using the mechanical machine based on a sinusoidal function oscillating between 200 and 1600 N at a frequency of 1.5 Hz. These values were representative of impact force observed during running. To examine stable characteristics, we analyse only the tenth cycle with the previous ones that are being used to stabilise the mechanical behaviour of the material (Sun et al., 2008).

The ST (in $\text{N} \cdot \text{mm}^{-1}$) of the sole was computed between 200 and 400 N according to Equation (1) where $U_{200 \text{ N}}$ and $U_{400 \text{ N}}$ represent the displacement of the stamp at force levels of 200 and 400 N, respectively (Schwanitz & Odenwald, 2008).

$$\text{ST} = (400 - 200)/(U_{400 \text{ N}} - U_{200 \text{ N}}) \quad (1)$$

The energy loss (E_{loss}) is a variable representative of the viscosity or capacity of the material to dissipate energy. Energy loss was computed according to Equation (2) where F represents the force, U the displacement, U_{max} and U_{min} the maximum and minimum displacements, respectively, and E_{input} and E_{return} the input and returned energies, respectively.

$$E_{\text{input}} = \int_{U_{\text{min}}}^{U_{\text{max}}} F(U) dU;$$

$$E_{\text{return}} = \int_{U_{\text{max}}}^{U_{\text{min}}} F(U) dU; E_{\text{loss}} = E_{\text{input}} - E_{\text{return}} \quad (2)$$

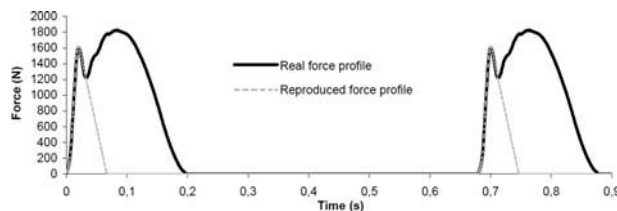


Figure 1. Force profile at 100% MAS. The black line represents the signal measured using the force platform. The grey dotted line represents the way the signal was implemented in Zwick machine to simulate impact on the heel part of the shoe.

Energy has been approximated using Simpson's rule method for numerical integration.

Table II. Summary of the mechanical characteristics of the 6 shoes used in the study.

	Viscous		Intermediate		Elastic	
	New	Fatigued	New	Fatigued	New	Fatigued
ST ($\text{N} \cdot \text{mm}^{-1}$)	165	189	130	146	87	126
E_{loss} (J)	2.35	2.15	2.31	1.88	1.92	1.62

Note: The general increase in ST and decrease in viscosity after aging, where ST ($\text{N} \cdot \text{mm}^{-1}$) represents the ST of the midsole computed on force deformation relation between 200 and 400 N and E_{loss} (J) represent the energy dissipation.

The mechanical properties of all 6 shoes (3 new and 3 fatigued) are summarised in Table II.

Biomechanical experimentation

Participants. Twelve healthy male participants (age: 26.0 ± 3.5 years, height: 177 ± 5 cm, mass: 75 ± 12 kg, US shoe size: 9.5) practising physical activity on a regular basis volunteered for participation in the experiment. All the participants provided written informed consent according to the Declaration of Helsinki (2002) before inclusion in this study, which was approved by the Local Committee for Human Protection in Biomedical Research.

Measurements. Six cameras of an optoelectronic motion capture system ([®]Vicon T40) and 40 retro reflective markers placed over the following landmarks: forehead, seventh cervical vertebrae, acromioclavicular joints, middle of the sternum length, anterior superior iliac spines, sacrum, greater trochanters, middle of the thigh on the lateral sides, middle of the thigh on the front side, lateral and medial condyle of the knees, head of fibulas, tibial tuberosity, middle of the lateral side of the legs, lateral and medial malleolus, calcaneus tuberosity, proximal and distal extremities of first and fifth metatarsus and hallux extremity were used to monitor the kinematics of the hip, knee and ankle joints as well as foot inversion at impact. All markers intended to be placed on foot anatomical landmarks were glued to the upper part of the shoe. Muscular activity of right lower limb tibialis anterior, peroneus longus, gastrocnemius medialis, gastrocnemius lateralis, vastus medialis, vastus lateralis and biceps femoris were measured using bipolar surface electromyography (EMG) electrodes ([®]Delsys Trigno System) located according to SENIAM recommendation after skin preparation (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Vertical ground reaction force was measured by a force platform ([®]Kistler 9281 CA). Right tibial acceleration was measured by a three-dimensional accelerometer ([®]Endevco Isotron 65HT, ± 50 g) fixed with glue on a balsa wood board ($20 \times 10 \times 2$ mm) itself glued on participants' skin

over the medial face of the tibia halfway between medial malleolus and medial tibial condyle. Data were recorded at 2000 Hz (except for the kinematics recorded at 125 Hz) and synchronised using Vicon Nexus Software (Vicon, Centennial, CO, USA).

Experimental protocol. After an explanation of the experimental design, participants performed three 5-s maximum voluntary isometric contractions in each of 5 positions. For ankle plantar (gastrocnemius medialis and gastrocnemius lateralis) and dorsal flexors (tibialis anterior), participants sat on a chair with their foot set into a shoe firmly fixed on the ground. The same position was used for eversion muscle (peroneus longus) but with the foot tilted 15° in inversion position. For knee extensor (vastus medialis and vastus lateralis) and flexor (biceps femoris) muscles, participants sat on a chair with knee joint immobilised at 90° . A rest time of 2 min was respected between each contraction.

Participants were asked to step down a staircase (height = 17 cm) with their right leg first, impact a force plate with the leg straight and the foot dorsiflexed and terminate the movement with the left leg towards a reception platform located 17 cm underneath the force plate. To study potential interaction effect between aging condition (cushioning capacity) and incline, the force plate was either flat (FL) or tilted to the right by 10° (relative to right foot) about the antero-posterior axis (IN), thus challenging foot inclination at impact. Indeed, after suffering damage caused by aging, the cushioning performance could differ in between the two incline conditions. After a few trials performed to allow for adaptation to the experimental situation, participants were requested to perform the task 5 times for each of the 12 experimental conditions resulting from the combination of the 6 mechanically characterised shoes (2 aging \times 3 material) and 2 inclines of the impact force plate. The order of testing was randomised for each participant.

Data analysis. A generic lower limb model was scaled to match the participant's anthropometric measurements based on experimentally measured marker positions from static poses. To reduce the

measurement errors due to marker movements on the participant's skin, we used an inverse kinematics algorithm to solve for the minimum difference between the experimental and the virtual markers (Delp et al., 2007). The outputs of this inverse kinematics step consisted in hip, knee and ankle joint angles through time.

EMG signals were first filtered with a second-order, bandpass Butterworth filter with cut-off frequencies of 10 and 450 Hz, rectified and filtered again using a low-pass Butterworth second-order 30-Hz filter (Robertson & Dowling, 2003) and then normalised by maximal values of maximum voluntary isometric contractions. Muscular pre-activations expressed in percentage of maximal voluntary activation (% maximal voluntary activation (MVA)) were computed as averaged muscle activation magnitudes from 100 ms before impact to the impact (Müller, Grimmer, & Blickhan, 2010).

Force and acceleration data were filtered (Butterworth, second-order, low-pass, cut-off frequency = 50 Hz) before the computation of the first peak of vertical ground reaction force, the loading rate and the tibial vertical acceleration peak and rate. Loading and acceleration rates were determined according to Duquette and Andrews (2010) as the slope of the force/acceleration–time profile from 20% to 80% of signal magnitude.

Statistical analysis. For all the above-described biomechanical dependent variables, the mean values over the 5 trials in each condition were calculated for each participant. Repeated measures by analysis of variance ([®]Statistica, Statsoft) were used to test the influence of the factors incline, aging and material. All significant effects ($P < 0.05$) were followed by Tukey post hoc tests.

Results

Mechanical experimentation

Before aging, the ST of the midsole and its capacity to dissipate energy were higher for the viscous shoe ($165 \text{ N} \cdot \text{mm}^{-1}$ and 2.35 J , respectively), intermediate for the intermediate shoe ($130 \text{ N} \cdot \text{mm}^{-1}$ and 2.31 J , respectively) and lower for the elastic shoe ($87 \text{ N} \cdot \text{mm}^{-1}$ and 1.92 J , respectively). As illustrated in Figure 2, the aging protocol increased the ST for all shoes (+14.5% for the viscous shoe, +12.3% for the intermediate shoe and +44.8% for the elastic shoe) and decreased their capacity to dissipate energy (−8.5% for the viscous shoe, −18.6% for the intermediate shoe and −15.6% for the elastic shoe).

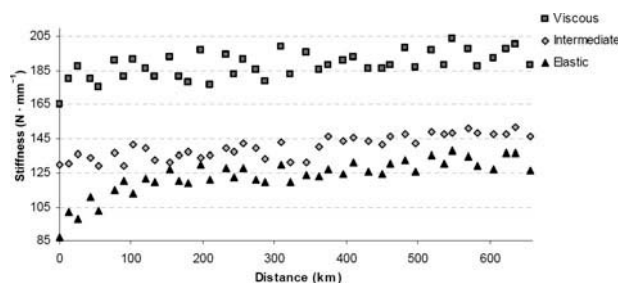


Figure 2. Evolution of the ST (in $\text{N} \cdot \text{mm}^{-1}$) of the viscous midsole (dark grey square), intermediate midsole (light grey diamond) and elastic midsole (black triangle) during simulated distance (km).

Measurement of the ST was performed before each aging session and after 24 h of rest for the last value. ST was computed between 200 N and 400 N.

Biomechanical experimentation

Kinematics. Concerning material and aging effect there was only very small or non-significant effect (Table III). Consequently, the task can be considered similar for all the experimental conditions. Platform inclination induced no effect on kinematics variable except for foot inversion which was higher ($F_{1,11} = 14.39$, $P < 0.05$) in FL than in inclined condition ($2.32 \pm 4.74^\circ$ vs. $0.75 \pm 5.01^\circ$).

Muscular pre-activation. There was no significant main effect of inclination ($F_{1,11} = 0.39$, $P > 0.05$), but a significant interaction of aging and material factors on vastus lateralis pre-activation ($F_{2,22} = 3.91$, $P < 0.05$) (Table III). The decomposition of the interaction into its simple main effects showed that for the elastic material, vastus lateralis pre-activation was higher ($F_{2,22} = 3.91$, $P < 0.05$) with the fatigued shoe than with the new shoe ($19.9 \pm 8.8\%$ MVA vs. $16.4 \pm 5.7\%$ MVA) (Figure 3(a)). The inclined condition generated higher biceps femoris pre-activation ($F_{1,11} = 8.81$, $P < 0.05$) and lower tibialis anterior pre-activation ($F_{1,11} = 12.81$, $P < 0.05$) than the FL condition. No other significant effect was observed on muscular pre-activation.

Tibial acceleration. Tibial acceleration peaks showed no significant main effect of incline ($F_{1,11} = 0.13$, $P > 0.05$), but showed significant effect of the interaction between material and aging factors ($F_{2,22} = 7.25$, $P < 0.05$) (Table III). The decomposition of the interaction into simple effects showed that for the elastic material acceleration peaks were greater after aging than before (Figures 3(b) and 4). Moreover, after aging the elastic material generated significant greater acceleration peaks than those generated by intermediate material, while there was no difference between the two materials before aging.

Table III. Mean values and standard deviations(s) of all variables for all the experimental conditions.

	Flat												Inclined												
	New						Fatigued						New						Fatigued						
	Viscous		Intermediate		Elastic		Viscous		Intermediate		Elastic		Viscous		Intermediate		Elastic		Viscous		Intermediate		Elastic		
	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	mean	s	
Hip flexion (°)	11.6	6.8	11.5	6.5	11.5	7.3	12.0	7.0	11.8	11.8	7.5	11.6	7.2	12.7	7.6	11.9	7.4	12.0	6.8	12.2	6.8	11.6	7.8	12.7	7.6
Knee flexion (°) ^A	4.0	2.1	3.6	2.2	4.0	2.2	3.5	2.1	3.2	3.2	2.3	3.5	2.1	3.8	2.1	3.9	2.8	4.3	2.5	3.9	2.6	4.0	2.0	3.7	2.6
Ankle flexion (°) ^M	26.2	4.9	25.7	4.7	25.9	5.0	26.1	4.7	25.6	25.6	4.6	25.6	4.6	26.1	4.6	25.3	4.5	25.8	4.4	25.8	4.5	25.4	4.4	25.6	4.6
Foot inversion (°) ^{A/M}	3.3	4.7	2.3	4.8	2.2	4.7	2.4	5.0	1.4	1.4	5.0	2.3	5.1	1.7	4.4	0.6	4.9	1.4	5.9	0.2	5.3	-0.3	5.0	0.8	5.3
PreTA (%MVA) ^I	36.1	6.1	36.6	7.1	36.0	6.5	37.3	7.8	37.5	37.5	8.8	37.9	6.2	34.6	6.8	34.1	5.4	34.5	6.4	36.0	5.0	32.3	10.4	35.7	6.0
PrePL (%MVA)	16.5	8.6	17.0	10.2	16.8	9.2	17.5	10.5	17.4	17.4	9.7	17.1	9.5	16.4	9.4	15.9	8.6	16.2	9.3	17.1	9.4	15.8	9.2	16.4	10.2
PreGM (%MVA)	1.8	0.9	1.9	0.9	2.3	1.5	2.4	1.5	1.9	1.9	0.9	1.8	0.9	1.8	1.0	1.7	0.9	1.8	0.8	1.8	0.9	1.7	0.9	1.7	1.0
PreGL (%MVA)	3.0	1.8	2.9	1.5	2.7	1.3	3.2	1.9	3.1	3.1	1.7	2.9	1.5	3.3	2.5	2.9	1.7	3.0	1.9	3.1	1.9	2.9	1.8	2.8	1.6
PreVM (%MVA)	13.0	10.4	14.7	10.1	13.6	9.9	14.7	12.1	14.5	14.5	9.9	12.9	8.3	11.0	6.1	10.6	8.1	10.4	6.4	10.4	6.7	10.0	5.7	13.5	8.7
PreVL (%MVA) ^{A/M}	17.5	6.5	18.7	6.2	16.5	4.9	18.2	6.6	19.6	19.6	7.6	19.0	7.8	18.4	10.4	15.7	7.3	16.3	6.7	16.6	7.9	17.2	8.8	20.8	10.0
PreBF (%MVA) ^I	4.7	3.3	4.4	1.8	4.3	1.9	5.0	3.2	4.6	4.6	2.2	4.8	2.8	5.3	2.4	5.5	3.5	5.1	2.6	5.6	3.1	5.1	2.3	5.3	2.4
PP (BW) ^I	2.03	0.27	2.08	0.27	2.15	0.27	2.05	0.25	2.15	2.15	0.27	2.09	0.28	1.89	0.29	1.95	0.41	1.94	0.30	1.90	0.32	1.91	0.35	1.90	0.39
LR (BW · s ⁻¹) ^M	57.4	16.5	51.1	14.2	52.0	13.0	55.2	14.3	56.4	56.4	14.8	54.1	15.3	58.7	21.6	56.6	22.3	49.8	15.3	62.8	23.7	53.5	21.4	56.8	23.3
AP (g · s ⁻¹) ^{A/M}	5.37	1.86	4.22	1.17	4.09	0.87	5.56	1.76	4.68	4.68	1.19	5.03	1.37	5.22	1.55	4.39	1.83	3.73	1.17	6.11	1.77	4.29	1.36	5.35	1.77
AR (g · s ⁻¹) ^{A/M}	299	236	278	137	249	129	415	221	313	313	162	345	164	414	224	301	202	232	146	517	276	304	172	400	226

Notes: The letters A, M and I after the variable name, respectively, indicate a significant effect of aging, midsole material and incline, and A/M a significant effect of interaction between aging and midsole material. All significant effects were considered at $P < 0.05$. Joint angle values are considered at impact. PreTA, PrePL, PreGM, PreGL, PreVM, PreVL, PreBF stands for pre-activations of the tibialis anterior, peroneus longus, gastrocnemius medialis, gastrocnemius lateralis, vastus medialis, vastus lateralis and biceps femoris muscles, respectively; PP = impact peak of the vertical ground reaction, LR = loading rate, AP = acceleration peak, AR = acceleration rate, MVA = maximal voluntary activation.

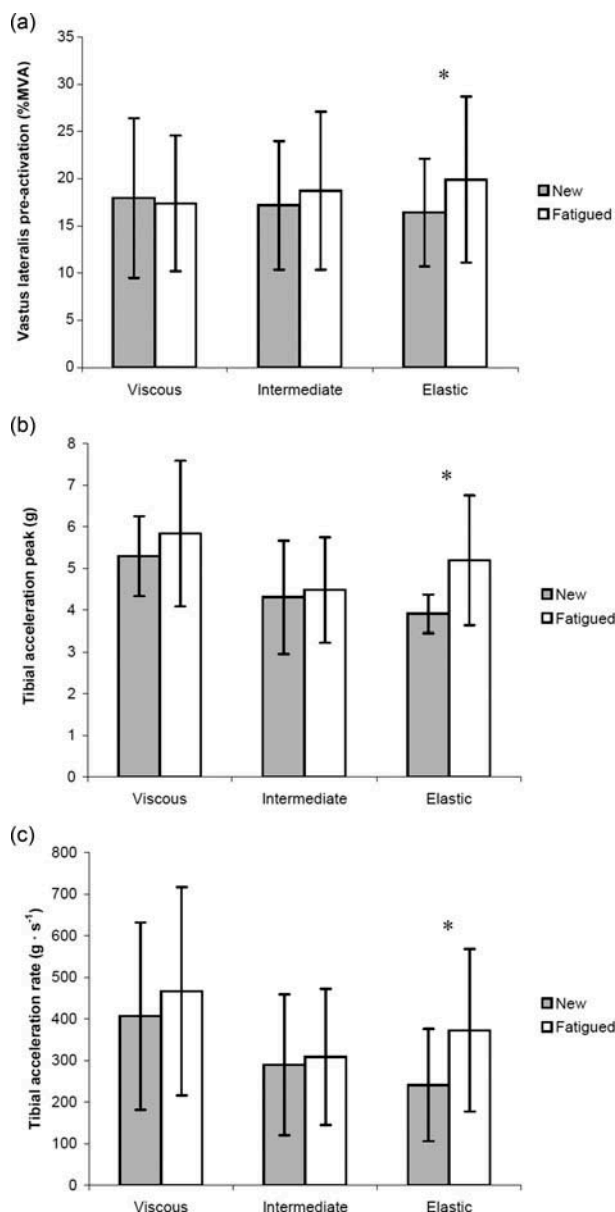


Figure 3. VL pre activation in % MVA (a), peak of tibial acceleration in g (b) and rate of tibial acceleration in $g \cdot s^{-1}$ (c) for the two aging conditions (mean \pm standard deviation) as a function of material condition.

*indicates a significant difference ($P < 0.05$) between new and fatigued conditions. Note the significant increase after aging of the three measured variables for Elastic material.

Tibial acceleration rates showed significant effect of the interaction of material and aging factors ($F_{2,22} = 7.45$, $P < 0.05$). The decomposition of the interaction into simple effects showed that for the elastic material acceleration rates were significantly greater after aging than before (Figures 3(c) and 4). Before aging, the viscous material generated significantly greater acceleration rates than those generated by elastic material while there were no differences between the two materials after aging.

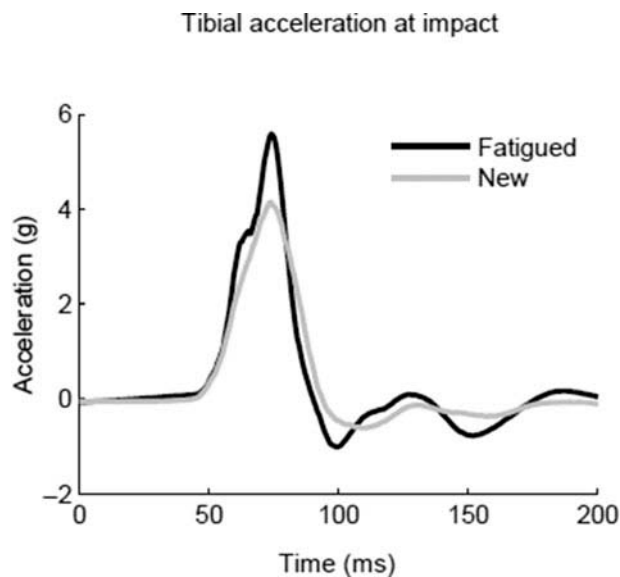


Figure 4. Tibial vertical acceleration of a representative subject during impact with fatigued (black) and new (grey) shoe for elastic material. Note the larger peak magnitude and acceleration rate for the fatigued condition.

Vertical ground reaction force. There was no material effect on first peak of vertical ground reaction force, but loading rate values were higher ($F_{2,22} = 5.52$, $P < 0.05$) with viscous material than with the elastic material ($58.5 \pm 19.0 \text{ BW} \cdot s^{-1}$ vs. $53.2 \pm 16.8 \text{ BW} \cdot s^{-1}$) (Table III). No aging effect was found on the vertical ground reaction force, but the first – passive – peak on vertical ground reaction force was significantly greater in FL condition ($2.09 \pm 0.26 \text{ BW}$) than in inclined condition ($1.91 \pm 0.33 \text{ BW}$) (*incline* effect: $P < 0.05$, $F_{1,11} = 12.27$).

Discussion

This study aimed first at elaborating a mechanical aging protocol and second at investigating the aging of running shoes in terms of ST and viscosity and its repercussions on biomechanical parameters (kinematic, dynamic and electromyographic data) at impact. The tested shoes were either new or fatigued and their midsoles were made out of viscous, elastic or intermediate materials. A better understanding of the mechanical and biomechanical effects of aging and material may allow us to optimise the running shoes, its cushioning function and durability in order to improve injury prevention.

Advanced-level runners should pay special attention to the aging of their shoes that can be influenced by various parameters such as the runner weight, speed, foot strike pattern and the type of ground he/she trains on. Our aging protocol, applying mechanical loading to the heel area of the midsole

based on a training plan, likely leads to a realistic aging state of heel area of the shoes as 80% of runners are rear-foot striker (Williams, McClay, & Manal, 2000).

Besides being realistic regarding the mechanical loading applied, the aging protocol designed for the present study has the advantage of being highly reproducible. Indeed, as opposed to previous studies in which shoe aging was performed by human participants in real conditions (Brueckner, Heidenfelder, Odenwald, & Milani, 2011; Heidenfelder et al., 2009), the aging protocol was implemented on a mechanical machine, thus avoiding the questions of long-term biomechanical adaptation and homogeneity in shoe's aging levels. Our results are consistent with the previous ones in which shoes were fatigued by human participants with decreased damping capacity (Cook, Kester, Brunet, & Haddad, 1985) and increased ST of the shoes with aging (Schwanitz, Möser, & Odenwald, 2010).

As expected from the literature (Brückner, 2010; Morio et al., 2009; Schwanitz & Odenwald, 2008), the mechanical aging influenced mechanical parameters of all shoes by increasing their ST and decreasing their capacity to dissipate energy. Interestingly, the influence of the aging protocol was not identical depending on the midsole material, with the ST increasing much more for the shoe with the elastic midsole (+45.6%) than for the two others.

This study was based on a standardised task aimed at limiting kinematics variability thus reducing participants' adaptations between conditions. Such a task was chosen to allow a measure of the real effect a shoe has on the biomechanical variables of interest and allow for a biomechanical evaluation of shoes' cushioning quality. Indeed it has been shown that mechanical characteristics of the interface at foot/ground contact had effects on hip, knee and ankle kinematics at impact (Hardin, van den Bogert, & Hamill, 2004). Lafortune et al. (1996) demonstrated the importance of lower limb kinematics configuration at the impact on tibial acceleration and vertical ground reaction force. While this standardised task has a lot of advantages for our questioning, the direct extrapolation to running activity has to be done with caution.

In line with the instructions, participants impacted the force plate with the leg straight and the foot in dorsiflexion. The observed differences of ankle and knee angle at impact between conditions were lower than 0.5° , and no difference was found at the hip; thus except for foot inversion movement, these results suggest that kinematic adaptation is unlikely to account for any differences observed between conditions (*midsole*, *aging* or *incline*). The aforementioned evolution of shoe mechanical properties as a

result of aging however had repercussions on the other biomechanical variables. Indeed, fatigued shoes induced higher acceleration peaks and rates, probably due to increased midsole ST as suggested by Lafortune, Lake, and Hennig (1996), Heidenfelder et al. (2010) and Morio et al. (2009). In line with previous studies, the stiffest material (viscous material) was the one inducing the highest tibial acceleration. However, neither aging nor material induced an effect on the first peak of vertical ground reaction force. Regarding aging, this result is consistent with the literature as Clarke and Frederick (1983), Nigg et al. (1987) and Heidenfelder et al. (2010) showed no effect of shoe cushioning on this variable. The sensitivity of the first peak of vertical ground reaction force to changes in material properties, however, remains questioned in the literature (Shorten & Mientjes, 2011). The fact that the tibial acceleration loading rate induced by the non-fatigued viscous shoe was higher than the one induced by the two other non-fatigued shoes could be explained by differences in material ST. Indeed, differences in ST before and after aging ($27 \text{ N} \cdot \text{mm}^{-1}$ on average) were lower than differences between the non-fatigued viscous and the other shoes ($70 \text{ N} \cdot \text{mm}^{-1}$ on average). It seems from these results that tibial acceleration is a more relevant variable than vertical ground reaction force to discriminate between shoe mechanical properties when kinematics is controlled.

As opposed to the previously discussed results that highlighted a strong link between midsole ST and biomechanical variables (acceleration loading rate), the link between energy loss and impact magnitude was not so clear. Results for the non-fatigued and the fatigued shoes indeed showed different trends, as the non-fatigued viscous shoe had the greatest energy loss and produced the greatest impacts while aging decreased energy loss values for all shoes but increased impact magnitude. Adapting shoes' viscosity thus does not necessarily help in reducing impact through the body. However, such a variable may possibly improve the midsole durability and is worth being looked at (Figure 2).

Before aging, acceleration peaks and rates for the elastic shoes were lower than those of intermediate shoes, while they became higher for the elastic shoe afterwards. Consistent with our hypothesis, it suggests that different shoe materials do not age the same way and affect the body differently at impact. In addition to the already monitored midsole ST, material durability should thus be considered as an important criterion to control during running shoe conception.

While it is possibly not a relevant variable to discriminate between midsole ST, vertical ground reaction force can discriminate other aspects like foot

landing strategies. Indeed, participants tended to impact with a foot positioned in a higher inversion position which induced significant greater (almost 10%) passive peak values (2.09 ± 0.26 BW) in FL condition relative to inclined condition (1.91 ± 0.33 BW). In inclined condition, the additional available degree of freedom (inversion/eversion movement) around the foot could allow for a slower impact than in FL condition.

Another result of this study was that shoe aging also affects muscular activity at impact, a variable known to also act as an active cushioning mechanism. Indeed, stiffer aged shoes caused significant greater vibration through the body. In response to these vibrations, muscular activities were modified to minimise soft tissue vibration (Boyer & Nigg, 2004; Verdejo & Mills, 2004b). The higher pre-activation of the knee extensor vastus lateralis muscle with aged shoes probably induce muscle stiffening, thus amplifying impact magnitude (Gerritsen, van den Bogert, & Nigg, 1995). This is particularly true for elastic shoe which shows 25% of muscular pre-activation augmentation after aging. Among all the muscles of the lower limb, the vastus lateralis is one of the muscles presenting the larger volume (Ward, Eng, Smallwood, & Lieber, 2009). The larger the mass of the wobbling structure, the more likely it is for the vibration to be harmful with respect to the resulting kinetic energy. The anatomical difference could explain the fact that for the type of studied task, only the vastus lateralis pre-activation was modified with aging.

This study investigated an aspect that may potentially increase injury risk: shoe aging. It was intended to notice and validate the direct effects of shoe aging on impact and to determine the most favourable shoe (among the three tested) to avoid development of injury due to cushioning aging. Indeed it is known that aging cause an increase of midsole ST. An increase of midsole ST can affect the vertical ground reaction force loading rate and the tibial acceleration, and an increase of tibial acceleration is associated with stress fracture apparition (Milner et al., 2006).

This study first proposed and validated a mechanical method for aging of the heel area of the shoe that could be used in future studies to obtain a similar aging level for all the compared shoes and thus, to validate running shoe in terms of cushioning and durability in a quick, reproducible and standardised way. By using this carefully controlled rear shoe aging protocol together with a standardised biomechanical task, this study then confirmed that the aging protocol affects mechanical properties of running shoe midsoles and that the aging of the shoe has an effect on the biomechanical variables used to characterise running activity. Among these modifications, the increase of ST is strongly suspected to

have an effect of impact magnitudes during running and thus potentially on increase of overuse injury rates (Taunton et al., 2003).

Durability in cushioning of running shoes is a real challenge in overuse injury prevention (Taunton et al., 2003). While the elastic shoe caused the lowest tibial acceleration rate and peak before the aging process, this shoe presented the largest increase of ST due to aging as well as increased tibial acceleration peak and rate. In this study, the intermediate material seemed to be the best compromise between cushioning and durability. Shoes used in this study had full ethylene-vinyl acetate midsole, but it is not the case of all running shoes. Other shoes which have specific cushioning concepts (gel, air cushion, polyurethane insert, rigid plastic piece, etc.) must be studied separately and cannot be used to bring forward general conclusions.

The biomechanical task used cannot attest the repercussions of midsole properties on running kinematics, and this study cannot by itself prove that shoe aging induces injury. An epidemiologic study designed with a longitudinal protocol is necessary to claim that. Further investigations are still to be done. Indeed, the present work focused only on heel contact, and the conclusions thus stands only for 80% of the runner population (i.e. rearfoot strikers). Future research should investigate the push-off phase after a realistic fatigue of rear and fore parts of the midsole.

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