23 Effects of Footwear on Muscle Function

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CONTENTS

23.1 INTRODUCTION

Footwear is a fundamental piece of clothing that is worn in most communities throughout the world. Footwear protects the foot from extraneous trauma, it can provide comfort, and it is also a fashion item. It addition, certain footwear, for example, running shoes, are purported to provide improvements in performance and reductions in injury. Footwear can have a significant effect on the musculoskeletal system and there has been a substantial amount of research relating to these effects. One area of the musculoskeletal system that footwear has an effect on is *muscle function*. This chapter, therefore, concentrates on the effects of footwear on muscle function. To ensure a comprehensive and transparent review of the literature on this topic, and to minimize bias in the selection of information, we systematically searched the literature to incorporate all relevant studies.

23.2 SYSTEMATIC LITERATURE REVIEW DETAILS

The following section presents details of how we searched for information relating to the effects of footwear on muscle function and the results of the search undertaken. Titles and abstracts from 390 studies were reviewed following a literature search of major databases (MEDLINE and CINAHL®). Of the studies reviewed, 34 investigated the *effect of footwear on lower limb muscle activity during walking or running* and were subsequently included in the evidence presented in this chapter.

The most common styles of footwear investigated were athletic or running style shoes (19 studies), high-heeled or negative-heeled shoes (7 studies), and rocker-sole and unstable style shoes (6 studies). Of these studies, 22 investigated participants during walking and 10 during running (including two that comprised both walking and running).

Muscle activity was generally assessed using two methods: (1) electromyography (EMG) and (2) muscle function magnetic resonance imaging (mfMRI). However, studies investigating the effect of footwear on muscle function have almost exclusively used EMG, except two studies that have used mfMRI. EMG usually involves mounting surface electrodes on the skin overlying individual muscles to sample the electrical activity evoked by motor units during muscular contraction. Occasionally, researchers will use indwelling electrodes to access deeper muscles within the body. In contrast, mfMRI involves the measurement of exercise-induced changes in muscle cell metabolism and muscle fluid uptake following exercise and is reflected by an increase in MRI signal intensity (O'Connor et al., 2006; Murley, 2008).

The advantage of using EMG over other modalities for assessing muscle activation, such as MRI or ultrasound, is the ability to investigate muscle activity simultaneously with dynamic weight-bearing tasks such as walking (Semple et al., 2009). This allows interpretation of muscle activity specific to different phases of the gait cycle. There is a wide range of EMG parameters reported in the literature that relate to muscle activity, including temporal (timing) and intensity variables. Temporal variables include onset, duration, and time to maximum activity. Intensity variables include wavelet analysis, integrated and normalized peak amplitude. Furthermore, EMG signals can be evaluated at a range of different stages of the gait cycle (e.g., preheel strike phase, propulsion phase, etc.), which provides important information on dynamic everyday tasks. (For additional technical information relating to EMG, readers are directed to the work by Cram and Criswell [2011]).

The following section presents a summary of the findings of studies investigating the effect of footwear on lower limb muscle activity. Where possible, the various styles of footwear are broadly classified and discussed according to shoe structure or a specific shoe feature (i.e., high-heeled and negative-heeled shoes). This chapter does not provide a systematic quality assessment (i.e., methodological quality) of the literature; for this, we redirect readers to the work of Murley et al. (2009).

23.3 DISCUSSION

The following section discusses the findings from the studies that were identified in our systematic search of the literature. To aid discussion, we categorized studies into four broad areas, with each representing a different type of footwear, including the following: (1) athletic or running shoes, (2) rocker-sole and unstable style shoes, (3) high-heeled and negative-heeled shoes, and (4) occupational-specific and other shoes. We now discuss the studies relating to each type of footwear.

23.3.1 Athletic or Running Shoes

Over several decades spanning back to the late 1980s, subtle variations in the properties of athletic footwear, such as alterations in heel counter stiffness (Jorgensen, 1990) and midsole density or stiffness (Komi et al., 1987; Wakeling et al., 2002; von Tscharner et al., 2003; Roy and Stefanyshyn, 2006) have been investigated almost exclusively during running. Various styles of athletic footwear have been used to investigate issues, such as the specific role of lower limb muscles (O'Connor and Hamill, 2004; O'Connor et al., 2006), differences between barefoot and shod running (Komi et al., 1987; Jorgensen, 1990; Ogon et al., 2001; von Tscharner et al., 2003; Divert et al., 2005), attenuation of muscle fatigue in those with overpronating feet (Cheung and Ng, 2010), and tuning of lower limb muscles through alteration in sensory input signals (Boyer and Nigg, 2004). The results of these studies are presented in Table 23.1.

23.3.1.1 Midsole Elasticity/Viscosity/Hardness

Researchers in this area of interest have primarily focused on investigating the potential to "tune" muscle activity by manipulating the impact force. In this instance, the impact force is manipulated through wearing shoes with midsoles of varying hardness, or no shoes at all (i.e., barefoot). Researchers speculate that tuning muscles by altering the input signal (i.e., impact force) could provide insight into the mechanisms that alter muscle activity during running, and as a consequence, may assist our understanding of the causes of lower limb injury.

Two studies used a process related to EMG wavelet analyses to quantify total EMG amplitude (von Tscharner et al., 2003) and EMG frequency characteristics (Wakeling et al., 2002) while comparing various running shoes with different midsole hardness or density. von Tscharner et al. (2003) found significantly greater EMG intensity for tibialis anterior preheel strike and lower intensity postheel strike with running shoes compared to barefoot. Wakeling et al. (2002) investigated the effects of running with a hard and soft insole in a small sample of six male and female runners. They reported significant changes in the intensity ratio between high- and low-frequency bands of selected muscles, although they did not report the post hoc findings for any muscle or shoe effects.

A further two studies investigated differences between barefoot and shod running (Ogon et al., 2001; Divert et al., 2005). Ogon et al. (2001) evaluated erector spinae (L_3) at jogging speeds in 12 healthy volunteers. They reported that jogging barefoot was associated with a significantly earlier onset during heel strike, however, a more prolonged latency to peak acceleration of the lower back during heel strike. The authors hypothesized that these findings reflect the benefits of running shoes in temporally synchronizing destabilizing external forces with stabilizing internal forces around the lumbar spine. Divert et al. (2005) investigated several lower leg muscles in 35 primarily male runners. In contrast

TABLE 23.1
Athletic or Running Shoes

Author/s (Date)	Participant Characteristics Age (Standard Deviation)	Footwear/Test Conditions	Muscles	Task	EMG Variables	Main Findings
Boyer and Nigg (2004)	10 Male subjects who exercised regularly Age: 25 (standard error 4.2) years	(Heel hardness—Asker C) (1) Elastic heeled shoe (52) (2) Viscous heeled shoe (50) (3) Viscoelastic (40) (4) Viscoelastic (55) (5) Viscoelastic (70)	Rec. femoris Bic. femoris Tib. anterior Med. gastroc	Running	Wavelet analysis (intensity derived from time and frequency)	No significant differences between conditions
Cheung and Ng (2009)	20 Novice female runners Age: 25.8 (±3.7) years	(1) Control "cushion" shoe (2) Motion-control shoe	Vast. medialis Vast. lateralis	Running	Onset of amplitude	Vast. medialis—significantly earlier onset relative to vast. lateralis with motion-control shoe compared to control "cushion" shoe
Cheung and Ng (2010)	20 Novice female runners Age: 25.8 (±3.7) years	(1) Neutral shoe (2) Motion-control shoe	Tib. anterior Per. longus	Running	Normalized RMS amplitude and median frequency	Per. longus and tib. anterior—significant positive correlation between RMS amplitude and mileage in the neutral shoe Per. longus—significantly larger drop in median frequency with neutral shoe

Divert et al. (2005)	35 Healthy runners (31 males, 4 females) Age: 28 (±7) years	(1) Barefoot (2) Standard running shoe	Tib. anterior Per. longus Med. gastroc Lat. gastroc Soleus	Running	Mean EMG amplitude	Med. gastroc, lat. gastroc, soleus—significantly greater amplitude with barefoot condition compared to running shoe
Jorgensen (1990)	11 Symptom-free heel strike runners (5 females, 6 males) Age: 25.5 years (range 14–37)[a]	(1) Barefoot (2) Athletic shoe with rigid heel counter (3) Athletic shoe with heel counter removed	Hamstrings[b] Quadriceps[b] Triceps surae[b] Tib. anterior	Running	Normalized EMG amplitude Time to peak amplitude No. of turns in EMG signal	Triceps surae and quadriceps—significantly earlier activity, greater amplitude and no. of turns with heel counter removed compared to shoes with rigid heel counter
Komi et al. (1987)	4 Males with “athletic background” Age: 32 (±9.4) years	(1) Barefoot (2), (3), and (4) ‘Jogging shoes” (5) and (6) “Indoor shoes” (indoor shoes comprised harder sole characteristics)	Rec. femoris Vast. medialis Lat. gastroc Tib. anterior	Running	Mean and integrated EMG	No significant differences between conditions
Nigg et al. (2003)	20 Male runners free from serious injury[a]	(1) Shoe with mainly elastic heel (shore C = 45) (2) Shoe with softer more viscous heel (shore C = 26)	Tib. anterior Med. gastroc Vast. medialis Hamstring group[b]	Running	RMS amplitude	No significant differences between conditions
O’Connor and Hamill (2004)	10 Males (“rearfoot strikers”) Age: 27 (±5) years	(1) Running shoe—neutral (2) Running shoe—medial wedge (3) Running shoe—lateral wedge (EVA rearfoot wedge tapered by 1 cm across heel of midsole + no heel counter on shoes)	Med. gastroc. Lat. gastroc Soleus Tib. posterior Tib. anterior Per. longus	Running	Integrated and mean EMG EMG onset and offset	No significant differences between conditions

(*continued*)

TABLE 23.1 (continued)
Athletic or Running Shoes

Author/s (Date)	Participant Characteristics: Age (Standard Deviation)	Footwear/Test Conditions	Muscles	Task	EMG Variables	Main Findings
O'Connor et al. (2006)	10 Male "rearfoot strikers" Age: 27 (±5) years	(1) Running shoe—neutral (2) Running shoe—medial wedge (3) Running shoe—lateral wedge (EVA rearfoot wedge tapered by 1 cm across heel of midsole + no heel counter on shoes)	Med. gastroc Lat. gastroc Soleus Tib. posterior Tib. anterior Ext. dig. longus Per. longus	Running	MRI transverse relaxation times (T2). Average of five slices through muscle belly (scan occurred 3.6 ± 0.3 min after run completed)	Tib. anterior—significantly less EMG activity with the neutral compared to varus shoe Soleus—significantly less EMG activity with the neutral compared to the varus and valgus shoe
Ogon et al. (2001)	12 healthy volunteers (7 males, 5 females) Age: 32.9 (±7.9) years	(1) Unshod (2) Shod (running shoes)	Er. spinae (L_3)	Running	Onset latency/timing	Er. spinae—significantly earlier onset with unshod condition compared to shod following heel strike Er. spinae—significantly shorter latency with shod condition compared to unshod following peak acceleration
Roy and Stefanyshyn (2006)	13 subjects with weekly mileage >25 km Age: 27 (±5.1) years	(1) Unmodified control shoe (2) Modified stiff shoe (3) Modified stiffest shoe	Vast. lateralis Rec. femoris Bic. femoris Med. gastroc Soleus	Running	RMS EMG amplitude from four intervals of stance phase	No significant differences between conditions

Serrao and Amadio (2001)	3 "runners" Age: 24.7 (±3.2) years	(1) Barefoot (2) Individuals' running shoes	Vast. lateralis Med. gastroc	Walking and running	Normalized mean EMG	Vast. lateralis—significantly delayed peak EMG with running shoes compared to barefoot (during walking and running) Med. gastroc—significantly delayed peak EMG with running shoes compared to barefoot (during walking only)
von Tscharner et al. (2003)	40 male "runners"; weekly mileage >25 km[a]	(1) Barefoot (2) Neutral running shoe (3) Pronation control running shoe	Tib. anterior	Running	Wavelet analysis (total EMG intensity)	Tib. anterior—significantly higher and significantly lower EMG intensity with running shoes[a] compared to barefoot during pre- and postheel strike periods of gait cycle
Wakeling et al. (2002)	6 "runners" (3 females) Age: 23.3 (±4.1) years (3 males) Age: 26.0 (±2.5) years	(1) Hard midsole running shoe (2) Soft midsole running shoe	Bic. femoris Rec. femoris Med. gastroc Tib. anterior	Running	Wavelet analysis (low- and high-frequency bands, preheel strike)	Muscles[b]—significantly altered[a] total EMG intensity with different midsole[a] hardness preheel strike

Posterior trunk: Er. spinae—erector spinae; *Anterior compartment thigh*: Rec. femoris—rectus femoris, Vast. lateralis—vastus lateralis, Vast. medialis—vastus medialis; *Posterior compartment leg*: Gastroc.—gastrocnemius, Med. gastroc.—medial gastrocnemius, Lat. gastroc.—lateral gastrocnemius, Flx. d. longus—flexor digitorum longus, Tib. posterior—tibialis posterior, Flx. h. longus—flexor hallucis longus; *Anterior compartment leg*: Tib. anterior—tibialis anterior, Ext. h. longus—extensor hallucis longus, Ext. d. longus—extensor digitorum longus; *Lateral compartment leg*: Per. longus—peroneus longus, Per. brevis—peroneus brevis.

[a] Muscle unspecified.

[b] No further information available.

to Ogon et al. (2001), this investigation reported EMG amplitude rather than temporal characteristics, and participants were assessed while running as opposed to jogging. When running barefoot, participants displayed significantly greater preactivation (EMG amplitude) for medial and lateral gastrocnemius and soleus. The authors suggested that this finding might indicate enhanced storage and restitution of elastic energy in these muscles.

There have been five other studies that have investigated the effect of athletic shoes with variable levels of midsole stiffness or density on similar muscle groups (i.e., thigh and lower leg); however, none reported any significant findings (Komi et al., 1987; Stefanyshyn et al., 2000; Nigg et al., 2003; Boyer and Nigg, 2004; Roy and Stefanyshyn, 2006). The discrepancies between these studies and those discussed earlier may be related to the relatively small sample sizes (leading to issues with statistical power). In addition, incomparable methods, particularly the different approaches to processing the EMG signal and the types of EMG parameters reported makes comparison between these studies difficult.

In summary, for midsole hardness, the findings from the aforementioned studies indicate that lower limb muscle activity can be "tuned" with shoes that have different hardness to accommodate the impact force at heel strike. Furthermore, the material hardness of the midsole may selectively activate specific muscle fiber types, with potential for implications on muscle fatigue and athletic performance.

23.3.1.2 Motion-Control Shoes

One of the key distinguishing features between different styles of modern athletic/running footwear is the density of the midsole. Footwear manufacturers generally produce a "neutral" or "cushioned" midsole for those with high-arched or rigid foot types and then a range of "motion-control" midsoles, with varying densities in the medial and lateral regions of the midsole (e.g., dual density), that aim to reduce pronation in those with flat-arched and hypermobile foot types.

With this in mind, some recent studies have investigated whether motion-control footwear, with a dual-density midsole, reduces lower leg muscle fatigue and restores quadriceps muscle timing in novice female runners with excessive foot pronation (Cheung and Ng, 2009, 2010). These studies found that when compared to a motion-control shoe, the neutral shoe is associated with significant positive gains in root mean square EMG amplitude with increasing running mileage for tibialis anterior and peroneus longus, and a larger decline in median frequency for peroneus longus. This indicates that there is greater fatigue in peroneus longus with a *neutral* shoe as running mileage increases. Another interesting finding from these studies is that motion-control shoes tend to normalize the onset of vastus medialis activation in those with excessive pronation, which may have implications for those with patellofemoral pain syndrome caused by the vastii muscle onset imbalance.

In summary, for motion-control shoes, only two studies have investigated the effect of this type of footwear on lower limb muscle activity. These studies indicate that motion-control shoes have a positive influence on (i.e., reduce) lower leg muscle fatigue and normalize vastii muscle onset in those with excessive foot pronation.

23.3.1.3 Midsole Wedging

Another variable that is thought to influence lower limb motion and muscle activity is the angulation of the shoe midsole. For example, the midsole can be made with a varus or valgus angulation. A varus wedged sole would be expected to reduce demand for muscles that support the medial column of the foot (e.g., tibialis posterior), while increasing demand on muscles that support the lateral column of the foot (e.g., peroneus longus). Perturbing the foot in this way may have clinical implications for individuals with dysfunction of specific muscles or joints (e.g., a varus wedged sole may reduce demand on the inverter musculature in a flexible flatfoot). In contrast, a valgus wedged sole would cause the opposite effect; that is, reduce demand on muscles that support the lateral column of the foot, while increasing demand on muscles that support the medial column of the foot.

With this in mind, two related studies have investigated the roles of the extrinsic foot muscles during running by manipulating the frontal plane angulation of the midsole (O'Connor and Hamill, 2004; O'Connor et al., 2006). The shoes used in these investigations featured (1) a flat midsole (with no angulation), (2) a varus-angled midsole, or (3) a valgus-angled midsole. The shoes with varus- and valgus-angled midsoles were intended to induce foot supination and pronation, respectively, during different stages of the gait cycle while running.

The investigators used EMG to record muscle amplitude and temporal parameters (O'Connor and Hamill, 2004; O'Connor et al., 2006), and muscle function MRI (O'Connor et al., 2006) to assess metabolic activity and workload of lower limb muscles. The EMG analysis indicated that the midsole with a varus angle significantly increased tibialis anterior EMG amplitude compared to the neutral midsole, while the neutral midsole significantly decreased the EMG amplitude for soleus compared to the varus- and valgus-angled midsoles. No significant differences between footwear conditions were detected from the mfMRI analysis.

In summary, for midsole wedging, there were some significant changes reported in these studies, although these findings are unexpected and inconsistent. Therefore, there is insufficient evidence at this stage that midsole wedging has a systematic effect on lower limb muscle activity.

23.3.1.4 Heel Counter

The heel counter (plastic reinforcement placed in the shoe upper around the heel) has been proposed to support the hindfoot and provide shock absorption through confinement of the fat pad of the heel (Jorgensen, 1990). These functions are presumed to alter the demand of lower limb muscles to control motion and attenuate shock. A single investigation of 11 asymptomatic heel-strike runners was undertaken using athletic shoes with and without a heel counter (Jorgensen, 1990). The findings from this study indicated that EMG amplitude for triceps surae and quadriceps occurred significantly later with the heel counter. The authors proposed that this finding could be due to increased shock absorption with the heel counter, leading to less demand for the leg and thigh muscles. Clearly, because there is only one study on this topic, further research is needed to determine the influence of the heel counter on lower limb muscle activity.

In conclusion, various characteristics of athletic or running style shoes influence lower limb muscle function. There is some evidence that altering the configuration

TABLE 23.2
Rocker-Sole and Unstable Style Shoes

	Participant Characteristics					
Author/s (Date)	**Age (Standard Deviation)**	**Footwear/Test Conditions**	**Muscles**	**Task**	**EMG Variables**	**Main Findings**
Bullock-Saxton et al. (1993)	15 Healthy adults (5 men, 10 women) Age: 18–20 years	(1) Barefoot (2) Balance shoes	Glut. maximus Glut. medius	Walking	Mean square value and rate of recruitment	Glut. maximus and medius—significantly greater activity and shortened time to maximum activity with balance shoes, compared to barefoot
Forestier and Toschi (2005)	9 Healthy subjects Age: 37.0 (±12.0) years	(1) Barefoot (2) Ankle destabilization shoe	Med. gastroc. Lat. gastroc. Tib. anterior Per. longus Per. brevis	Walking	Integrated and normalized Onset time (Per. longus and brevis only)	Tib. anterior, Per. brevis, and Per. longus—significantly greater EMG amplitude with destabilization shoe compared to barefoot
Nigg et al. (2006b)	8 healthy subjects (3 females, 5 males) Age: 28.0 (±3.6) years	(1) Unstable shoe (2) Control shoe	Glut. medius Bic. femoris Vast. medialis Med. gastroc. Tib. anterior	Walking	Wavelet analysis (total EMG intensity)	No significant differences between conditions

Peterson et al. (1985)	15 Healthy adult women Age: 25.5 (range) 21–30 years	(1) Rocker shoe with rigid wooden sole and open heel (2) Subjects own athletic shoes made of canvas or leather and laced up	Vast. lateralis Gastroc[a] Soleus	Walking	Timing of muscle activity	No significant differences between conditions
Romkes et al. (2007)	12 Healthy subjects (6 females, 6 males) Age: 38.6 (±13.2) years	(1) Individuals' regular shoes (2) Masai Barefoot Technologies® (MBT-shoes)	Sem. tend. Rec. femoris Vast. lateralis Vast. medialis Med. gastroc. Lat. gastroc. Tib. anterior	Walking	RMS from 16 equal intervals over gait cycle (normalized from barefoot condition)	Tib. anterior, Med. gastroc, Lat. gastroc, Vast. lateralis, Vast. medialis, and Rec. femoris—significantly greater RMS EMG activity with MTB-shoes compared to regular shoes (during part of contact phase) Tib. anterior, Med. gastroc, Lat. gastroc. significantly greater and Rec. femoris significantly lower RMS EMG with MTB-shoes compared to regular shoes (in part of swing phase)
Stoggl et al. (2010)	12 Healthy students (6 males, 6 females) Age: 25 (±2) years	(1) Running shoe (2) Unstable (MBT) shoe	Bic. femoris Vast. medialis Vast. lateralis Med. gastroc Tib. anterior Per. longus	Walking	Integrated EMG, RMS amplitude, median power frequency	No significant differences between conditions

Gluteal region: Glut. maximus—gluteus maximus, Glut. medius—gluteus medius; *Posterior compartment thigh*: Sem. tend.—semitendinosis, Sem. memb.—semitendinosis, Bic. femoris—biceps femoris, Lat. hamst.—lateral hamstring; *Anterior compartment thigh*: Rec. femoris—rectus femoris, Vast. lateralis—vastus lateralis, Vast. medialis—vastus medialis; *Posterior compartment leg*: Gastroc.—gastrocnemius, Med. gastroc.—medial gastrocnemius, Lat. gastroc.—lateral gastrocnemius, Flx. d. longus—flexor digitorum longus, Tib. posterior—tibialis posterior, Flx. h. longus—flexor hallucis longus; *Anterior compartment leg*; Tib. anterior—tibialis anterior, Ext. h. longus—extensor hallucis longus, Ext. d. longus—extensor digitorum longus; *Lateral compartment leg*; Per. longus—peroneus longus, Per. brevis—peroneus brevis.

[a] Muscle unspecified.

and material properties of a shoe midsole can have an effect on lower limb muscle activity. Studies investigating shoes with differing midsole hardness have demonstrated a phenomenon described as "muscle tuning," whereby muscle activity is tuned to minimize soft tissue vibration and reduce fatigue. This has been speculated to be a mechanism that protects the lower limb from injury; however, further research is required to tease out this issue. Motion-control features influence lower leg muscle fatigue and vastii activation patterns in those with excessively pronated feet. Finally, one study found that a heel counter significantly alters lower limb muscle activity.

23.3.2 Rocker-Sole and Unstable Style Shoes

Rocker-sole shoes are designed to assist forward momentum of the body over the foot by having a rounded (convex) sole that is curved in an anterior–posterior direction. Like a rocker-sole shoe, unstable shoes feature a similar anterior–posterior curvature, but they are also curved in a medial–lateral direction. The purpose of including both anterior–posterior and medial–lateral curves is to induce instability via the uneven surface of the sole of the shoe, which supposedly mimics barefoot locomotion (Landry, 2011). It is thought that the uneven surface challenges lower leg muscles that may otherwise be underused when wearing more stable, traditional footwear. Therefore, the unstable shoe design is intended to strengthen lower leg muscles and it is thought that this can reduce pain for a range of musculoskeletal conditions, including knee joint osteoarthritis and low back pain. Recent studies provide limited evidence supporting the use of unstable shoes for these conditions, compared to more supportive, traditional footwear (Nigg et al., 2006a, 2009). The results of the studies included in this section are presented in Table 23.2.

In terms of altering muscle activity, the earliest study of a rocker-sole shoe was conducted by Peterson et al. (1985) on 15 healthy women. The rocker-soled shoe, which featured a rigid wooden sole and open heel, was compared to the participants' own athletic shoes. No significant differences in vastus lateralis and triceps surae EMG muscle timing were detected.

Following on from this work, Bullock-Saxton et al. (1993) investigated the effect of walking with "balance shoes" (i.e., unstable shoes) in 15 healthy participants. They assessed the effect of balance shoes on gluteus maximus and medius and compared the shoes to a barefoot condition. They reported significantly greater gluteus maximus and medius activity and shortened time to maximum muscle activity with balance shoes. While this finding indicates greater work undertaken by the gluteal muscles with balance shoes, it is unclear whether this was due to the effect of the unstable sole or simply because of increased weight of the balance shoe. This is always a significant issue when comparing shoes to a barefoot condition or shoes of differing weight.

More recently, one study (Forestier and Toschi, 2005) used a mechanical destabilization device under the heel of a shoe while walking to induce destabilization of the rearfoot in nine healthy participants. A significant increase in tibialis anterior, peroneus longus, and peroneus brevis EMG amplitude was reported with the destabilization shoe compared to barefoot. Again, this device was compared to a barefoot condition, so the findings may just be related to the weight of the shoe.

Three other studies (Nigg et al., 2006b; Romkes et al., 2006; Stoggl et al., 2010) have compared the effect of unstable shoe design to either participants' own shoes (Romkes et al., 2006) or running shoes (Nigg et al., 2006b; Stoggl et al., 2010). Unfortunately, sample sizes in these studies were generally low, ranging from 8 to 12. Nevertheless, the first study by Romkes et al. (2006) reported that the unstable shoe significantly altered root mean square EMG amplitude of rectus femoris, vastus medialis, vastus lateralis, tibialis anterior, medial, and lateral gastrocnemius within defined intervals of stance and swing phase. The second study by Nigg et al. (2006b) also recorded EMG from gluteus medius, biceps femoris, vastus medialis, medial gastrocnemius, and tibialis anterior and found no significant changes in total EMG amplitude using wavelet analysis. The third study by Stoggl et al. (2010) investigated almost identical muscles to those of Romkes and colleagues; however, in this study the investigators were interested in whether variability of muscle activity was altered, rather than just direction changes in muscle amplitude or frequency. There were no significant differences comparing the unstable shoe to the running shoe condition.

In conclusion, for rocker-sole or unstable shoes, there is limited evidence that this type of footwear has a systematic effect on lower limb muscle activity during walking. The lack of significant findings may be attributed to factors such as the small sample sizes (and possibility of type 2 statistical errors), the style of control shoe used for comparison, and the types of EMG variables evaluated. That is, the unstable shoe design may influence muscle activity, however, previous studies have been limited in their design and have not been able to clearly demonstrate such an effect. There is, therefore, a need for further research on the efficacy of unstable shoe designs and destabilization devices to determine whether they produce predictable and consistent changes in muscle activity.

23.3.3 High-Heeled and Negative-Heeled Shoes

23.3.3.1 High-Heeled Shoes

The high-heeled shoe is a very popular style of fashion footwear. It is a unique style of shoe that is known to be associated with a range of foot deformities, including bunions and claw toes. High-heeled footwear has also been found to produce alterations in lower limb joint mechanics and plantar pressures (Stefanyshyn et al., 2000). While there are several features that characterize the high-heeled shoe such as a narrow and shallow toe-box, the elevation of the heel is a distinguishing feature, which in some shoes can reach 10 cm in height (Stefanyshyn et al., 2000).

The effect of differing heel height on muscle activity in females has been investigated in several studies, with heel heights ranging from 0 to 8 cm (Joseph, 1968; Lee et al., 1990; Stefanyshyn et al., 2000; Lee et al., 2001; Gefen et al., 2002; Park et al., 2010). The results of these studies are presented in Table 23.3. By systematically increasing the heel height, Lee et al. (2001) clearly demonstrated consistent increases in peak EMG for erector spinae activity in the back (i.e., a systematic effect). Increasing heel height is also associated with decreased medial gastrocnemius and tibialis anterior peak EMG amplitude (Lee et al., 1990) and increased rectus femoris, soleus, and peroneus longus root mean square EMG amplitude (Stefanyshyn et al., 2000). In contrast to these findings, one earlier study reported no significant

TABLE 23.3
High-Heeled and Negative-Heeled Shoes

	Participant Characteristics					
Author/s (Date)	**Age (Standard Deviation)**	**Footwear/Test Conditions**	**Muscles**	**Task**	**EMG Variables**	**Main Findings**
Gefen et al. (2002)	8 Female subjects 4 Habitual wearers of high-heeled shoes 4 Habitual wearers of flat-heeled shoes Age: 26.0 (±4) years	(1) Barefoot (2) "Own" footwear[a] (3) Fatiguing exercise 1 (4) Fatiguing exercise 2	Med. gastroc. Lat. gastroc. Soleus Per. longus Tib. anterior Ext. hall. longus	Walking	Normalized EMG median frequency	Med. and Lat. gastroc.—significantly faster decrease in median EMG frequency for Lat. gastroc relative to Med. gastroc. in habitual high-heeled wearers (after fatiguing exercises) compared to low-heeled wearers Per. longus—significantly faster decrease in median EMG frequency for habitual high-heeled wearers

Joseph (1968)	6 Subjects[a]	(1) Low-heeled shoes (heel height 1–2.5 cm) (2) High-heeled shoes (heel height 5.5–8 cm)	Er. spinae Glut. maximus Glut. medius Bic. femoris Hip flexor[b] Soleus Tib. anterior	Walking	Duration of EMG activity Raw EMG amplitude	No significant differences between conditions
Li and Hong (2007)	13 Female subjects Age: 23.1 (±3.9) years	(1) Normal shoes (2) Negative-heeled shoes	Er. spinae Rec. abdominus Bic. femoris Rec. femoris Lat. gastroc. Tib. anterior	Walking	Mean and integrated EMG Duration of EMG	Bic. femoris, Lat. gastroc., and Tib. anterior—significantly greater EMG amplitude; Lat. gastroc and tib anterior—significantly longer duration with negative-heeled shoe compared to normal shoe
Lee et al. (2001)	5 Healthy young women ("in their twenties")[a]	(1) Low-heeled shoes (0 cm) (2) Medium-heeled shoes (4.5 cm) (3) High-heeled shoes (8 cm)	Er. spinae (L_1/L_2) Er. spinae (L_4/L_5) Vast. lateralis Tib. anterior	Walking	Peak and integrated EMG	Er. spinae (L_4/L_5)—significantly greater peak EMG as heel height[a] increased
Lee et al. (1990)	6 Women ("regular wearers of high-heeled shoes") Age range: 20–31 years[a]	(1) Barefoot (2) 2.5 cm heeled shoes (3) 5.0 cm heeled shoes (4) 7.5 cm heeled shoes	Tib. anterior Med. gastroc.	Walking	Normalized peak and mean peak EMG	Med. gastroc and Tib. anterior—significantly lower mean peak EMG with 2.5, 5.0, and 7.5 cm heeled shoes compared to barefoot Med. gastroc—significantly lower mean peak EMG with 2.5 and 5 cm compared to 5.0 and 7.5 cm heeled shoes, respectively Tib. anterior—significantly greater mean peak EMG with 2.5 cm compared to both 5.0 and 7.5 cm

(*continued*)

TABLE 23.3 (continued)
High-Heeled and Negative-Heeled Shoes

Author/s (Date)	Participant Characteristics: Age (Standard Deviation)	Footwear/Test Conditions	Muscles	Task	EMG Variables	Main Findings
Park et al. (2010)	17 Healthy women Age: 22.1 (±1.2) years	(1) Barefoot (2) 3 cm high-heeled shoe (3) 7 cm high-heeled shoe	Vast. med. obliq. Vast. lateralis	Walking	RMS amplitude	Vast. med. oblq. to Vast. lateralis—significantly reduced ratio with the 7 cm heel compared to both the 3 cm heel and barefoot conditions
Stefanyshyn et al. (2000)	13 Female subjects Age: 40.6 (±8.3) years	(1) Flat shoe (1.4 cm heel height) (2) Low-heeled shoe (3.7 cm) (3) Medium-heeled shoe (5.4 cm) (4) High-heeled shoe (8.5 cm)	Sem. tend. Bic. femoris Rec. femoris Vast. medialis Gastroc[b] Soleus Tib. anterior Per. longus	Walking	RMS EMG amplitude	Per. longus, Rec. femoris, and soleus—significantly greater RMS EMG with higher-heeled shoes compared to lower-heeled shoes[c]

Posterior trunk: Er. spinae—erector spinae; *Anterior trunk*: Rec. abdom.—rectus abdominus; *Gluteal region*: Glut. maximus—gluteus maximus, Glut. medius—gluteus medius; *Posterior compartment thigh*: Sem. tend.—semitendinosis, Sem. memb.—semitendinosis, Bic. femoris—biceps femoris, Lat. hamst.—lateral hamstring; *Anterior compartment thigh*: Rec. femoris—rectus femoris, Vast. lateralis—vastus lateralis, Vast. medialis—vastus medialis; *Posterior compartment leg*: Gastroc.—gastrocnemius, Med. gastroc.—medial gastrocnemius, Lat. gastroc.—lateral gastrocnemius, Flx. d. longus—flexor digitorum longus, Tib. posterior—tibialis posterior, Flx. h. longus—flexor hallucis longus; *Anterior compartment leg*; Tib. anterior—tibialis anterior, Ext. h. longus—extensor hallucis longus, Ext. d. longus—extensor digitorum longus; *Lateral compartment leg*; Per. longus—peroneus longus, Per. brevis—peroneus brevis.

[a] No further information available.

[b] Muscle unspecified.

[c] Several post hoc findings.

changes in various thigh and lower leg muscles comparing heel heights of 1–2.5 to 5.5–8.0 cm (Joseph, 1968) although this study was performed in the 1960s. The reason for this contrary finding may be that the process of collecting and processing EMG data today is vastly progressed compared to when Joseph conducted his research.

The most recent study by Park et al. (2010) investigated barefoot and 3 and 5 cm heel heights in 17 healthy women. They found that increasing heel height decreased vastus medialis oblique EMG amplitude as a ratio of vastus lateralis activity, although this finding was only observed in the nondominant limb. As such, the meaning of this finding is unclear, but the authors suggest that it may assist with understanding potential mechanisms contributing to patellofemoral pain in women.

Finally, a slightly different approach to investigating the effects of high-heeled shoes was undertaken by Gefen et al. (2002). Rather than investigating the immediate effects of heel height on muscle activity, they compared the median EMG frequency of lower limb muscles from habitual and nonhabitual wearers of high-heeled shoes following a fatiguing exercise. When compared to habitual low-heel wearers, habitual high-heel wearers displayed a significantly faster decrease in median frequency for peroneus longus and lateral gastrocnemius after completing a fatiguing exercise. These findings may have been associated with the participants displaying reduced stability, and as a result, lead to an increased risk of accidental injury.

In conclusion, high-heeled shoes have a systematic effect on back and lower limb muscle activity. Even when high-heeled shoes are removed from one's feet, those who wear them regularly display greater fatigue characteristics for some lower leg muscles, and this may predispose them to accidental injury.

23.3.3.2 Negative-Heeled Shoes

In contrast to the high-heeled shoe style discussed earlier, Li and Hong (2007) compared negative-heeled shoes to normal-heeled shoes. They found that the negative-heeled shoes caused significantly greater EMG amplitude for biceps femoris, tibialis anterior and lateral gastrocnemius, and longer EMG duration for lateral gastrocnemius and tibialis anterior. In light of these findings, the authors suggest that negative-heeled shoes could assist with exercise rehabilitation or training programs, where inclined training surfaces are not available. Clearly, further research is needed for this style of shoe.

23.3.4 Occupational-Specific and Other Shoes

Various other footwear styles have been investigated for their effects on lower limb muscle activity. Three studies have investigated specific occupational-related footwear styles, primarily to identify specific shoe characteristics to reduce muscle fatigue and work-related musculoskeletal injury. These studies have featured shoes with various midsole stiffness properties in the following occupations; waiters (Kersting et al., 2005), those wearing clean room boots (rubber boot with polyurethane or polyvinyl chloride [PVC] sole) (Lin et al., 2007) and nurses (Chiu and Wang, 2007). The results of these studies are presented in Table 23.4.

TABLE 23.4
Occupational-Specific and Other Shoes

	Participant Characteristics					
Author/s (Date)	**Age (Standard Deviation)**	**Footwear/Test Conditions**	**Muscles**	**Task**	**EMG Variables**	**Main Findings**
Bohm, and Hosl (2010)	15 Healthy males Age: 29 (±5) years	(1) Stiff shaft boot (2) Soft shaft boot	Sem. tend Vast. lateralis Tib. anterior Med. gastroc Per. longus	Walking	Cocontraction index of muscle amplitude	Vast. lateralis and Sem. tend.—significantly increased cocontraction between muscles in the stiff-shafted boot condition occurred during single leg stance
Bourgit et al. (2008)	12 Healthy females Age: 24 (±4) years	(1) Standard fitness shoe (2) Special 2° dorsiflexion	Glut. max. Vast. lateralis Rec. femoris Bic. femoris	Walking and running	Normalized RMS EMG amplitude	Knee extensors, Bic. femoris, Tib. anterior, and plantar flexors—significantly altered comparing several combinations of shoes for ballistic plantar flexion exercise Plantar flexors—significantly altered comparing several combinations of shoes for walking exercise

		(3) Special 4° dorsiflexion (4) Special 10° dorsiflexion	Tib. anterior Lat. gastroc Med. gastroc Soleus			Knee extensors and plantar flexors—significantly altered comparing several combinations of shoes for running exercise
Chiu and Wang (2007)	12 "Healthy" females Age: 23.3 years (±2.1) years	(1) Nursing shoe A (2) Nursing shoe B (3) Nursing shoe C (A, B, and C had different sole, midsole, upper and innersole characteristics)	Bic. femoris Rec. femoris Med. gastroc. Tib. anterior	Walking	Mean normalized EMG amplitude	Med. gastroc—significantly lower EMG amplitude with shoe A and shoe B compared to shoe C (shoe A and B included an arch support design[a])
Cho et al. (2007)	10 Participants over 50 years of age with plantar fasciitis (5 males, 5 females)	Microcurrent shoe (A specially constructed shoe of piezoelectric material that generates a microcurrent during loading)	Tib. anterior Soleus	Walking	Median peak frequency	Tib. anterior—significant reduced median peak frequency pre- and posttesting
Hansen et al. (1998)	8 Healthy women Age: 24 (range: 21–29) years	(1) Clogs without a heel (2) Sports shoe	Er. spinae (L_3)	Walking	RMS amplitude and mean power frequency	No significant differences between conditions
Kersting et al. (2005)	16 Trained waiters (8 males, 8 females) Male age: 27.9 (±2.3) years Female age: 23.9 (±2.0) years	(1) Standard shoe with stiff midsole (2) Neutral shoe with flexible midsole (3) Shoe with soft midsole	Er. spinae (L_3) Med. gastroc Tib. anterior Per. longus	Walking	Integrated EMG (iEMG)	Per. longus and Med. gastroc.—significantly greater iEMG with the shoe with a stiff midsole compared to the soft midsole when walking on a PVC surface Er. spinae—significantly higher activation for the stiff midsole shoe compared to the flexible midsole

(*continued*)

TABLE 23.4 (continued)
Occupational-Specific and Other Shoes

Author/s (Date)	Participant Characteristics: Age (Standard Deviation)	Footwear/Test Conditions	Muscles	Task	EMG Variables	Main Findings
Lin et al. (2007)	12 Healthy female students Age: 24.2 (±1.9) years	(1) "Clean room" boot A (2) "Clean room" boot B (3) "Clean room" boot C Each with different shock-absorbing and elastic properties	Er. spinae Bic. femoris Rec. femoris Gastroc.[b] Tib. anterior	Walking	Mean normalized EMG amplitude	Gastrocnemius[b]—Significantly greater EMG amplitude with boot C and B compared to boot A as a function of time
Sacco et al. (2010)	21 Healthy nondiabetic participants Age: 50.9 (±7.3) years 24 diabetic neuropathic participants Age: 55.2 (±7.9) years	(1) Barefoot (2) Own habitual shoes (sport shoes, loafers, sandals, dress shoes)	Vast. lateralis Lat. gastroc. Tib. anterior	Walking	Time to peak EMG	Lat. gastroc.—significant delay in diabetic participants with wearing habitual shoes compared to barefoot Vast. laterals—significant delay in nondiabetic participants with wearing habitual shoes compared to barefoot

Posterior trunk: Er. spinae—erector spinae; *Gluteal region*: Glut. maximus—gluteus maximus, Glut. medius—gluteus medius; *Posterior compartment thigh*: Sem. tend.—semitendinosis, Sem. memb.—semitendinosis, Bic. femoris—biceps femoris, Lat. hamst.—lateral hamstring; *Anterior compartment thigh*: Rec. femoris—rectus femoris, Vast. lateralis—vastus lateralis, Vast. medialis—vastus medialis; *Posterior compartment leg*: Gastroc.—gastrocnemius, Med. gastroc.—medial gastrocnemius, Lat. gastroc.—lateral gastrocnemius, Flx. d. longus—flexor digitorum longus, Tib. posterior—tibialis posterior, Flx. h. longus—flexor hallucis longus; *Anterior compartment leg*; Tib. anterior—tibialis anterior, Ext. h. longus—extensor hallucis longus, Ext. d. longus—extensor digitorum longus; *Lateral compartment leg*; Per. longus—peroneus longus, Per. brevis—peroneus brevis.

[a] No further information available.

[b] Muscle unspecified.

The first study investigated three shoes with varying midsole stiffness during walking in 16 trained waiters (Kersting et al., 2005). For peroneus longus and medial gastrocnemius, there was significantly greater integrated EMG (i.e., greater overall muscle effort) with the stiff-midsole shoe compared to the soft-midsole shoe. In addition, erector spinae exhibited significantly greater activation for the stiff-midsole shoe compared to the flexible-midsole shoe.

The second study investigated clean room boots with variable shock-absorbing and elastic properties under different walking conditions (e.g., carrying a load) (Lin et al., 2007). Gastrocnemius EMG amplitude was significantly lower with heavier, more elastic, and shock-absorbing boots when analyzed over time (i.e., after 60 min of walking). This finding indicates that varying the properties of clean room boots can influence muscle activity, but individuals need to be monitored for a long enough period of time (i.e., to induce some fatigue) to detect significant differences.

The third study evaluated three styles of nursing shoes with differing sole, midsole, upper, and innersole characteristics on 12 nurses (Chiu and Wang, 2007). The study found that shoes with "arch support" produced a significant decrease in medial gastrocnemius EMG amplitude. For the findings in these three studies to make clinical sense, EMG changes need to be linked to changes in health status. Ideally, future research needs to factor in symptomatic participants and measure patient reported outcomes, in addition to EMG changes over time.

Several other styles of footwear have been investigated for their effect on lower limb muscle activity; however, these styles cannot readily be classified with those mentioned earlier. These include a study comparing "standard fitness shoes" to a range of "special dorsiflexion" shoes (Bourgit et al., 2008), a "microcurrent" shoe for individuals with heel pain (Cho et al., 2007), clogs and sports shoes (Hansen et al., 1998), barefoot and shod muscle activity in individuals with and without diabetes related neuropathy (Sacco et al., 2010), and a comparison between stiff- and soft-shafted hiking boots (Bohm and Hosl, 2010). The results of these studies are also presented in Table 23.4.

In conclusion, there are too few studies to draw conclusions about the effects of specific occupational shoes on lower limb muscle activity. With the increasing need to create safe, ergonomically sound workplace environments, it is likely that there will be a rapid increase in research exploring the effect of occupational-specific footwear on muscle activity.

23.4 CONCLUSIONS

Footwear is an important piece of clothing that can have a significant effect on the musculoskeletal system, including muscle activity. In this chapter, we have systematically reviewed the literature to comprehensively and transparently cover the effect of footwear on muscle function. While there is a great deal of work yet to be done in this area, there have already been some exciting in-roads made. For example, there is some evidence that muscle activity can be tuned and that indicators of muscle fatigue can be manipulated by varying the composition of the midsole of athletic shoes. In addition, high-heeled shoes have a consistent effect on back and lower limb muscles.

However, clear deficiencies in the literature limit the conclusions that can be made about the wider effects of footwear on muscle function. There is a need for further research of more rigorous methodological quality, including larger sample sizes and greater consensus regarding reporting of electromyographic parameters. In addition, it is still not clear whether changes in muscle function with the use of some types of footwear are consistent and predictable (i.e., systematic), and it is currently not known whether an increase or decrease in EMG variables is beneficial in relation to injury and health status. While it makes intuitive sense that an intervention would be beneficial if it can bring muscle activity closer to that seen in a nonpathological population (measured via EMG), definitive evidence is still lacking.

In closing, therefore, there is some evidence that certain types of footwear can affect muscle function; however, there is insufficient evidence to make conclusions about the effect of footwear on clinically relevant conditions.

QUESTIONS

23.1 Discuss the limitations of the research related to the effects of footwear on lower limb muscle function.

23.2 Suggest ways in which research evaluating the effect of footwear on muscle function could be altered to improve the quality of evidence relating to this area of investigation.

23.3 Summarize the effects of varying the composition of the midsole of athletic shoes on muscle function.

23.4 Is there evidence to support the assertion that current running shoe technologies improve running performance?

23.5 Discuss the evidence related to the effects of high-heeled footwear on lower limb muscle activity.

23.6 Discuss the evidence related to the effects of rocker-sole and unstable footwear on lower limb muscle activity.

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