European Journal of Applied Physiology (2019) 119:2701–2710
https://doi.org/10.1007/s00421-019-04245-z

ORIGINAL ARTICLE

The effects of compression stockings on the energetics and biomechanics during walking

Longfei Cheng[1] · Caihua Xiong[1]

Received: 15 May 2019 / Accepted: 17 October 2019 / Published online: 25 October 2019

Abstract

Purpose The purpose of this study was to explore how compression stockings affect the energetics and biomechanics during walking.

Methods Sixteen male adults participated in this study. Participants completed walking trials on the treadmill and force plates, wearing compression stockings (CS) or nothing as a control condition (CON). The data obtained included metabolic rate, muscle activation, step frequency and step length as well as their variability, joint kinematics and joint kinetics.

Results The effect of compression stockings on metabolic rate was trivial (CS: 3.81 ± 0.44 W kg^{-1}, CON: 3.83 ± 0.46 W kg^{-1}, $p = 0.84$, $d = 0.05$). Activation of calf muscles, step frequency and step length as well as their variability, joint range of motion and joint powers did not show a significant difference between conditions ($p = 0.09$–0.90, $d = 0.01$–0.34). The peak knee extension moment during the early stance phase had a tendency to increase (CS: 0.57 ± 0.27 N m kg^{-1}, CON: 0.51 ± 0.28 N m kg^{-1}, $p = 0.05$, $d = 0.19$) while the peak knee flexion moment during the late swing phase had a tendency to decrease (CS: 0.16 ± 0.10 N m kg^{-1}, CON: 0.19 ± 0.12 N m kg^{-1}, $p = 0.10$, $d = 0.21$). The peak ankle dorsiflexion moment during the early stance phase significantly increased (CS: 0.11 ± 0.06 N m kg^{-1}, CON: 0.08 ± 0.05 N m kg^{-1}, $p = 0.02$, $d = 0.58$) while the peak ankle plantar flexion moment during the late swing phase significantly decreased (CS: 1.41 ± 0.12 N m kg^{-1}, CON: 1.47 ± 0.14 N m kg^{-1}, $p = 0.02$, $d = 0.45$).

Conclusions Compression stockings have a limited effect on improving energetics of walking, but they may play a role in improving biomechanics by altering the relative contribution of knee and ankle moments to propulsion.

Keywords Compression garment · Muscle activation · Kinematics · Kinetics · Metabolic cost

Abbreviations

CG	Compression garment
EMG	Electromyography
GL	Gastrocnemius lateralis
MVC	Maximal voluntary contraction
RER	Respiratory exchange ratio
RMS	Root mean square
ROM	Range of motion
SD	Standard deviation
SOL	Soleus
TA	Tibialis anterior

Introduction

Compression garments (CGs), of which the pressure gradually decreases from the distal to the proximal, have been widely used in medicine and sports. Researchers have found some physiological benefits of CGs, e.g., improving venous hemodynamics (Ibegbuna et al. 2003), increasing the deep tissue oxidation and metabolite clearance (Agu et al. 2004; Rider et al. 2014). These physiological benefits may contribute to improving the recovery after exercises (Brophy-Williams et al. 2017) or the recovery from muscle damage induced by exercises (Jakeman et al. 2010). Some mechanical benefits were also verified. For example, CGs can support the belly of muscles and reduce the muscle vibration (Doan et al. 2003). From the perspective of athletic

Communicated by Lori Ann Vallis.

✉ Caihua Xiong
chxiong@hust.edu.cn

[1] Institute of Robotics Research, State Key Lab of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China

performance, some garment manufacturers claimed that CGs can contribute to the improvement of athletic performance. Several studies indeed documented that CGs can improve the performance of some exercises (Doan et al. 2003; Kemmler et al. 2009). For instance, Broatch et al. (2018) found higher peak power during repeated sprint cycling. However, most studies did not show positive consequences during varieties of exercises or in varieties of environments (Driller and Halson 2013; Barwood et al. 2013; Doan et al. 2003; Areces et al. 2015; Duffield and Portus 2007). Chatard (1998) even found a negative effect of compression tights on exercise performance, where a 31 s longer time was observed during 5000 meters running. Undoubtedly, results varying among existing studies cannot provide convincing support for manufacturers' assertions.

This study focused on the potential for the improvement from the perspective of energetics and biomechanics rather than the athletic performance directly. Energetics and biomechanics can affect the performance of some exercises (Conley and Krahenbuhl 1980; Bartlett 1999) and both of them have been widely used in the studies about human movement (Voloshina and Ferris 2015; Kang et al. 2002). In terms of energetics of walking, humans can continuously optimise the metabolic cost per se (Selinger et al. 2015) and researchers have been trying to further improve the metabolic efficiency (Collins et al. 2015). Likewise, it is of significance to investigate the effect of CGs on gait biomechanics, e.g., surface electromyography (EMG), kinematics and kinetics. First, EMG has been widely applied to study muscle activation by reflecting the recruitment of motor units and muscle fibres conduction velocity (Orizio 1992). It can be used to monitor muscle fatigue (Tarata 2003) and explore the relationship with the muscle force (De Luca 1997), and it is also related to energy cost (Dean and Kuo 2011). Second, empirical studies have found that deviations from preferred gait require more metabolic cost (Selinger et al. 2015) and the deviations can also affect the comfort (Mündermann et al. 2003). Thus, there is a need to determine whether CGs interfere with the human natural gait. Third, joint kinetics plays a role in understanding the contributions of joints to the propulsion during gait, thus helping to avoid injuries (Kepple et al. 1997; Bartlett 1999).

To our knowledge, the estimation of CGs in previous studies was often based on the physiological parameters [such as venous return, blood lactate, heart rate and oxygen consumption (Agu et al. 2004; Ali et al. 2010)], psychological parameters [such as rating of perceived exertion and muscle soreness (Areces et al. 2015; Rider et al. 2014; Treseler et al. 2016)] and exercise performance [such as running time and time to exhaustion (Del Coso et al. 2014; Dascombe et al. 2011)]. Given the relationship between oxygen consumption and energy cost (Brockway 1987), previous studies related to oxygen consumption can be considered as a part of the studies regarding the energetic effect. Thus, although quite a few studies have explored the effect on energetics, the result shows great differences among them. An early study reported decreased energy cost when comparing compression tights with conventional shorts during running at some submaximal intensities (Bringard et al. 2006). In contrast to Bringard et al., Dascombe et al. (2011) found that wearing compression tights increased oxygen consumption during running at low-intensity speeds. A recent study, however, reported no difference in oxygen consumption between wearing compression socks and the control condition (Brophy-Williams et al. 2019). Taken together, these results suggested the need to further explore the effect on energetics. As for biomechanics, only a few studies investigated the effect on biomechanics, and these studies just involved certain one or two aspects of biomechanics. For example, Stickford et al. (2015) just measured kinematics related to gait parameters, while Fu et al. (2012) mainly focused on the muscle characteristics. But these energetic and biomechanical parameters are closely relevant to each other. For example, muscle activation can partly account for the energetics, and the joint moment can be a comprehensive result of muscle forces, gravity and inertial forces. Thereby, systematic study of energetics and biomechanics is necessary to deeply understand the mechanism of potential improvement.

The aim of this study was to explore the effects of compression stockings on metabolic cost, muscle activation, kinematics and joint kinetics during walking. Considering the physiological and mechanical benefits suggested by the previously published studies, we expected an improvement in energetics, muscle efficiency and joint kinetics while kinematics could be unaffected.

Methods

Participants

Sixteen healthy male adults (mean ± SD, height: 1.708 ± 0.049 m, weight: 63.5 ± 6.9 kg, age: 22.5 ± 0.9 years) volunteered to participate in the experiment. All participants did not have any musculoskeletal injuries or gait defects according to their self-reports which included current physical condition and relevant case histories. The experimental protocol was approved by the Huazhong University of Science and Technology Committee, and informed consent was obtained from all participants. The maximum and minimum girths of the calf were measured to follow the garment manufacturer's recommendations to choose appropriate stocking size. Participants were requested to abstain from food for 2 h prior to testing, and not to drink stimulating beverage (e.g., coffee, tea and alcohol) or perform any strenuous exercises for 24 h prior to testing. Except that tight shorts were worn for the convenience of attaching retroreflective markers to the body, shirts and shoes were the participant's own.

Experimental design

There were two conditions in the experiment, including a control condition without compression stockings (CON) and a treatment condition with the compression stockings providing a pressure of 30–40 mmHg (CS). The compression stockings, composed of 72% polyamide and 28% lycra, reached from the location above the ankle to that below the tibial tuberosity.

The experiment was divided into three sessions, including a training session and two testing sessions. In the first session, participants were instructed to walk on a treadmill (Trackmaster, Newton, Kansas, USA) at a speed of 5 km h^{-1} for at least 5 min. Then they practised walking on the force plates (AMTI, Watertown, MA, USA) following a metronome under two conditions. Four force plates with a sampling rate of 1000 Hz were serially placed, and at each moment only one foot can step on each force plate to separate forces on the two feet. The purpose of this session was to ensure that participants could familiarize themselves with the treadmill and force plate walking under two conditions. The second session performed on the treadmill aimed to measure the metabolic cost, EMG and kinematics. Participants were instructed to walk with their preferred step frequency and step length at a speed of 5 km h^{-1} for 6 min. The third session was the force plate walking trials. Participants were instructed to walk along a 10 metres level walkway following a metronome. The frequency was consistent with that of the treadmill walking trial, and it was calculated as the reciprocal of the averaged gait cycle time during the last minute. The gait cycle was segmented by the marker on the right heel. It was suggested that heel-strike occurred when the marker moved to the anterior-most position. Each condition had 15–25 trials. Two conditions were performed in random order with a break of at least 5 min between trials to reduce the effect of fatigue.

Data collection and analyses

The acquired data included metabolic rate, EMG, kinematics (i.e., step frequency and step length as well as their variability, joint angle of the hip, knee and ankle) and joint kinetics (i.e., joint moment and power of hip, knee and ankle). All the measurements were based on the treadmill walking trials except the joint kinetics which was calculated from the force plate walking trials.

The metabolic rate was measured via an indirect calorimetry system (Oxycon Mobile, CareFusion, Höchberg, Germany) according to a modified Brockway equation (Brockway 1987). The basal metabolic rate was measured when participants stood quietly for 6 min. The total metabolic rate was calculated from the last 3 min of each trial. The net metabolic rate obtained by subtracting the basal metabolic rate from the total metabolic rate was normalised to the body weight. The respiratory exchange ratio (RER) was monitored during the entire process to ensure that it was within the aerobic domain (RER $<$ 1) and trials not satisfying the requirement were abandoned.

EMG data were measured by the surface EMG sensors (SX230, Biometrics, Newport, UK) that have integral electrodes with a fixed distance of 20 mm, and the sampling rate is 1000 Hz. Muscles, to which the pressure was applied, were measured, including the tibialis anterior (TA), gastrocnemius lateralis (GL) and soleus (SOL). The electrodes were attached to the right leg. The position of electrodes was determined by SEMINAM guidelines (Hermens et al. 1999). To reduce impedance, we carefully prepared participants' skins, including shaving and cleaning with alcohol. The raw signal was amplified by an amplifier with a bandwidth of 20–460 Hz. Following the full-wave rectification, EMG data were filtered using a Butterworth filter with a cut-off frequency of 6 Hz to get a linear envelope. Lastly, EMG data were normalised to the peak amplitude of the CON condition and a gait cycle. EMG data were taken the same time as the kinematic data for further statistical analyses. The root mean square (RMS) value was calculated during the whole gait cycle.

Kinematic data were measured from the treadmill walking trials by a motion capture system with 10 cameras (MX T160, Vicon, Oxford, UK), and the sampling rate is 100 Hz. Sixteen retroreflective marker positions were determined according to the built-in plug-in gait lower body model. Kinematic data of half a minute during the last minute in the treadmill trials were processed, and we only focused on the data in the sagittal plane. The raw trajectories of markers were filtered using Woltring fifth spline algorithm with an MSE of 10. The method of gait segmentation was also according to the marker on the right heel. Step frequency was calculated by taking the reciprocal of the averaged gait cycle time. Step length was defined as the distance between two markers on heels along the propulsion direction when the heel-strike occurred. Gait variability was represented by the standard deviation (SD).

Kinetic data were obtained from the force plate walking trials. According to the speed and step frequency calculated from the software Nexus (Vicon, Oxford, UK), 5–15 optimal trials were chosen to be analysed. The closer the speed and step frequency of one trial were to the target speed and step frequency set by metronome, the more optimal the trial was. Unlike the treadmill walking trials, gait segmentation of the force plate walking trials was according to the ground reaction forces. It was thought that the heel struck the ground when the force exceeded the threshold of 20 Newtons. Joint moments and joint powers were calculated via inverse dynamics by the software Nexus. Joint moments were analysed only in the sagittal plane while joint powers were the sum of three individual planes. To better reflect the change in joint moments and joint powers, peak joint moment and peak joint power were further analysed. Peak hip moments were defined as the peak extension moment during the early stance phase and the peak flexion moment during push-off. Peak knee moments were defined as the peak extension moment during the early stance phase and peak flexion moment during push-off. Peak ankle moments were defined as the peak dorsiflexion moment during the early stance phase and the peak plantar flexion moment during push-off. Peak hip powers and peak ankle powers were defined as the peak positive power and the peak negative power during the late stance phase and the initial swing phase. Peak knee powers were defined as the peak positive power during the mid-stance phase and the peak negative power during the late swing phase. Also, the positive moment represented the extension moment while the negative moment represented the flexion moment for hip and knee joints. The positive moment represented the plantar flexion moment while the negative moment represented the dorsiflexion moment for ankle joint.

Statistical analyses

One participant's EMG data of TA were discarded due to the malfunction of electrodes. All data analyses were performed by the mathematical software Matlab (Mathworks, Natick, MA, USA). Data of a gait cycle would be excluded as outliers if they were out of the range of mean ± 3 SDs for any time point during the whole gait. Paired *t* test was applied for metabolic rate, RER, RMS of EMG, step frequency and step length as well as their variability, joint range of motion (ROM), the peak joint moment and the peak joint power between two conditions. To quantify the difference between conditions, Cohen's d effect size was calculated by dividing the difference between two conditions by pooled SD. Likewise, the difference in speed and step frequency was tested using the same method between treadmill walking and force plate walking. All significance levels were set at $\alpha = 0.05$. Effect sizes were deemed small ($d = 0.2$), medium ($d = 0.5$) and large ($d = 0.8$). All data were reported as mean ± SD unless otherwise stated.

Results

RER was comparable between conditions (standing: 0.87 ± 0.04, CS: 0.89 ± 0.05, CON: 0.90 ± 0.05, $p = 0.08$–0.90, $d = 0.03$–0.52). There was a trivial effect on the metabolic rate when wearing compression stockings as compared with the CON condition (CS: 3.81 ± 0.44 W kg^{-1}, CON: 3.83 ± 0.46 W kg^{-1}, $p = 0.84$, $d = 0.05$, Fig. 1a). But individual responses to the compression stockings varied across participants. Figure 1b shows the change of metabolic rate in CS condition relative to CON condition for every participant. Most participants presented a neutral response to the compression stockings, and only a few participants showed a major difference.

Activation of TA, GL and SOL during a gait cycle is shown in Fig. 2a. The activation patterns of all three muscles were basically consistent between conditions. As shown in Fig. 3a, RMS of EMG was not significantly different between conditions for TA (CS: 0.32 ± 0.05, CON: 0.31 ± 0.05, $p = 0.25$, $d = 0.16$), GL (CS: 0.29 ± 0.04, CON: 0.29 ± 0.03, $p = 0.30$, $d = 0.21$) and SOL (CS: 0.32 ± 0.04, CON: 0.32 ± 0.03, $p = 0.81$, $d = 0.04$).

Similarly, the influence of compression stockings on kinematics was limited. Step frequency and step length as well as their variability were not significantly different between

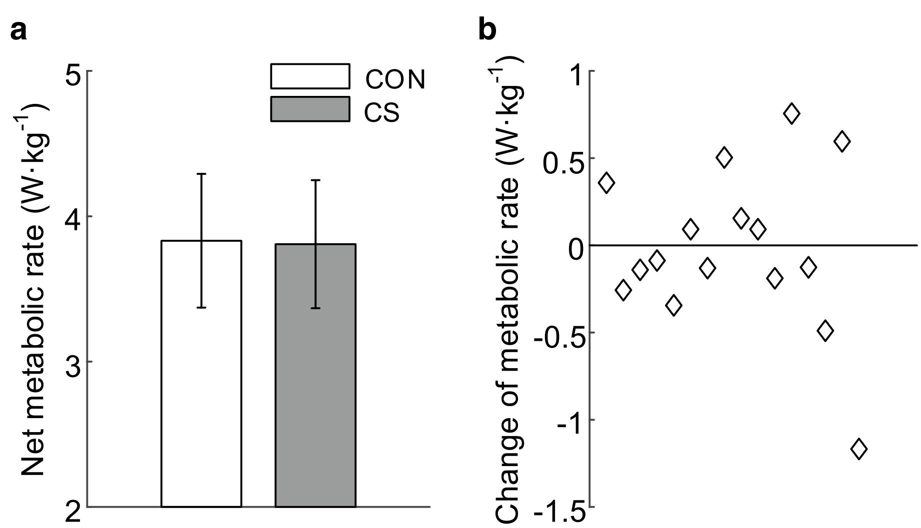
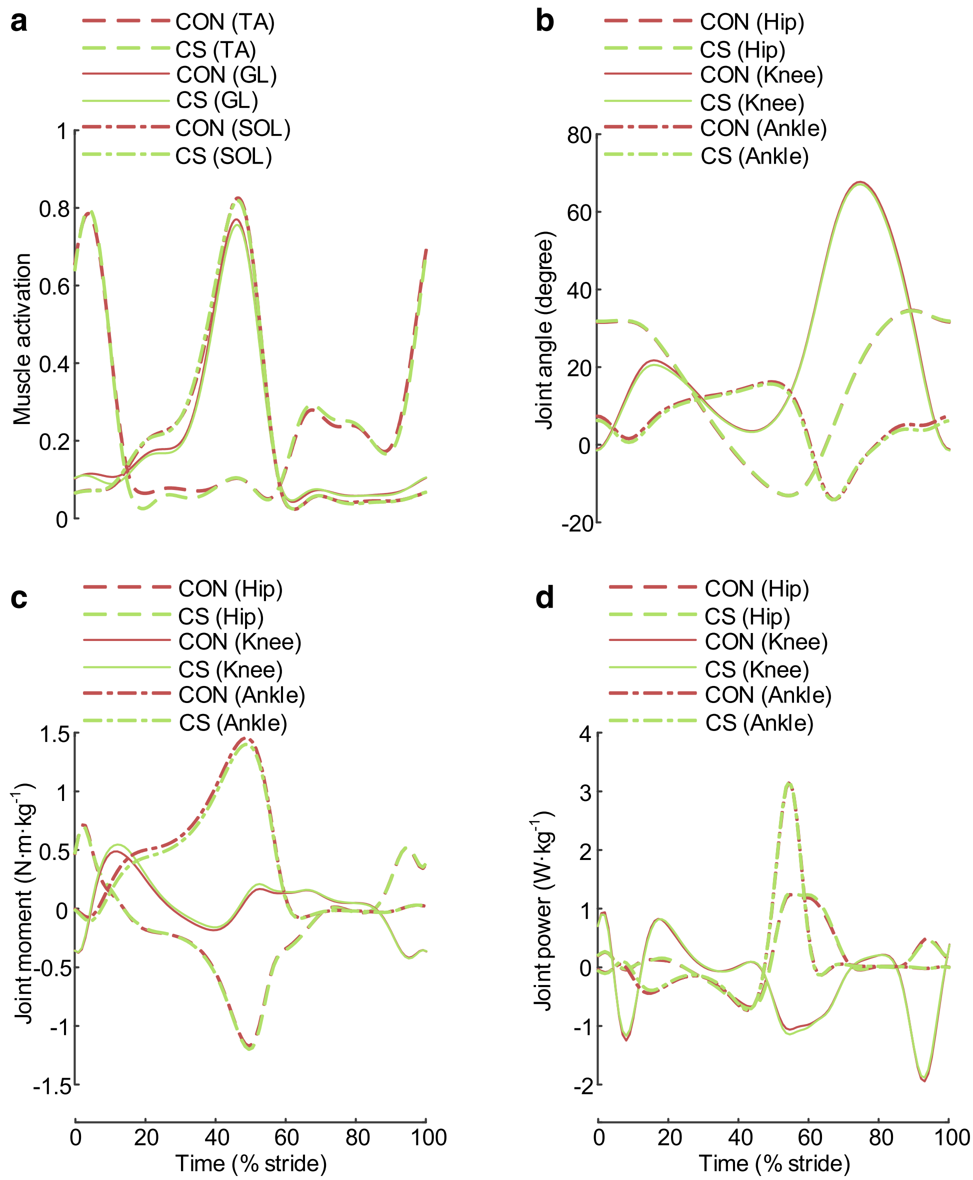


Fig. 1 Average metabolic rate under two conditions (**a**) and change of the metabolic rate in CS condition relative to the CON condition for every participant (**b**). Each diamond represents a participant's data

Fig. 2 EMG of tibialis anterior (TA), gastrocnemius lateralis (GL), and soleus (SOL) (**a**), joint angles (**b**), joint moments (**c**) and joint powers (**d**) of hip, knee and ankle during a gait cycle under CON and CS conditions. The dark red represents the CON condition and the shadow green represents the CS condition



two conditions ($p = 0.09$–0.90, $d = 0.01$–0.34, Table 1). Joint angle during a gait cycle is shown in Fig. 2b. Hip angle was almost unaffected. Knee and ankle angles showed a slight difference in certain phases. But ROM of three joints did not show significant differences ($p = 0.18$–0.58, $d < 0.2$ for all three joints, Fig. 3b).

Kinetic data were calculated from the force plate walking trials. The average walking speed was 1.23 ± 0.07 and 1.23 ± 0.06 m s^{-1} for CON and CS condition, respectively ($p = 0.35$, $d = 0.06$). The average step frequency was 1.9832 ± 0.0578 and 1.9898 ± 0.0508 Hz for CON and CS condition, respectively ($p = 0.37$, $d = 0.12$). Joint moments and joint powers during a gait cycle are shown in Fig. 2c, d. Joint powers of three joints and joint moments of hip in the CS condition were almost in line with those in the CON condition. But the knee and ankle joint moments presented a visible difference between two conditions. Difference can be more obvious from the peak joint moment and the peak joint power, as shown in Fig. 3c, d. During the early stance phase, the peak knee extension moment had a tendency to increase (CS: 0.57 ± 0.27 N m kg^{-1}, CON: 0.51 ± 0.28 N m kg^{-1}, $p = 0.05$, $d = 0.19$), and the peak ankle dorsiflexion moment significantly increased (CS: 0.11 ± 0.06 N m kg^{-1}, CON: 0.08 ± 0.05 N m kg^{-1}, $p = 0.02$, $d = 0.58$). Similarly, during push-off, the peak knee flexion moment tended to decrease (CS: 0.16 ± 0.10 N m kg^{-1}, CON: 0.19 ± 0.12 N m kg^{-1}, $p = 0.10$, $d = 0.21$), and the peak ankle plantar flexion moment significantly decreased (CS: 1.41 ± 0.12 N m kg^{-1}, CON: 1.47 ± 0.14 N m kg^{-1}, $p = 0.02$, $d = 0.45$). The peak hip extension and flexion moments did not have significant differences between conditions ($p = 0.14$, 0.30, $d < 0.2$). The peak positive and negative joint powers were of no

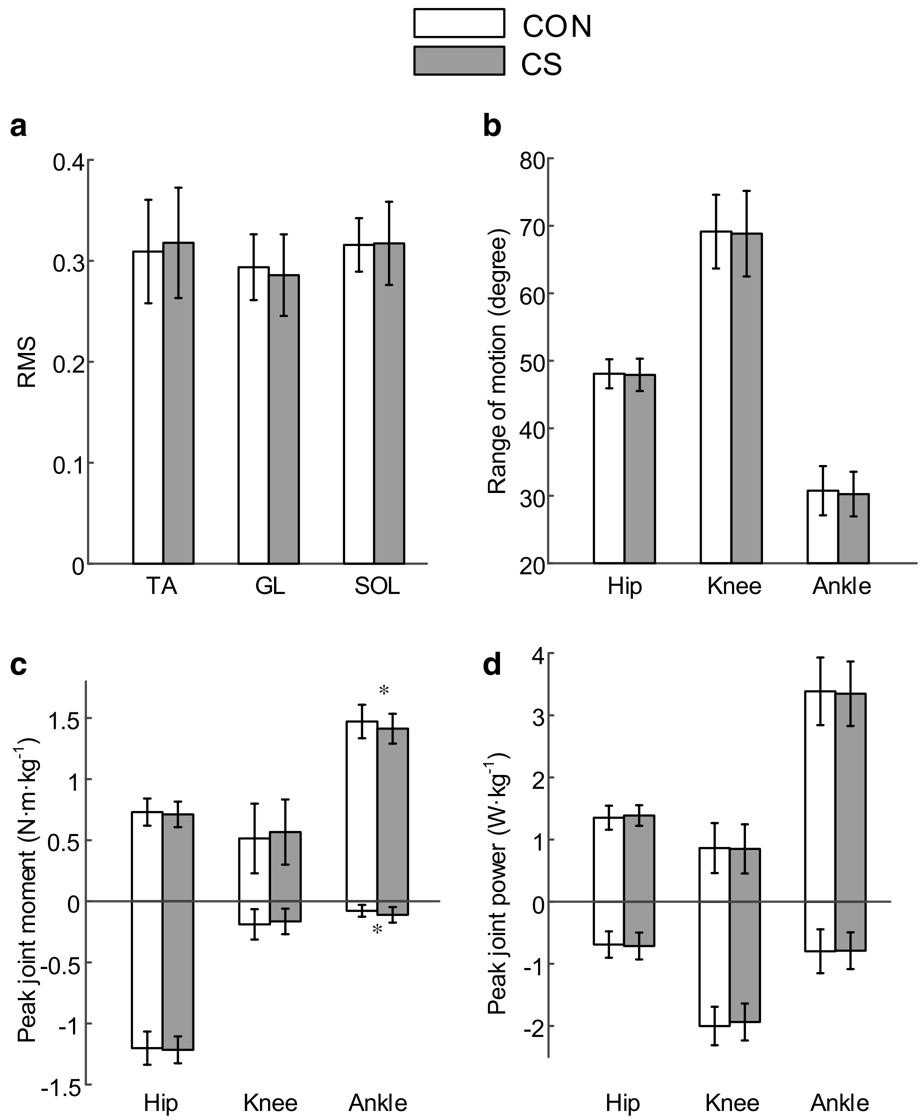


Fig. 3 Root mean square (RMS) of tibialis anterior (TA), gastrocnemius lateralis (GL), and soleus (SOL) (**a**), range of motion (ROM) (**b**), peak joint moment (**c**) and peak joint power (**d**) of hip, knee and ankle under CON and CS conditions. Data are represented as mean (bars) and SD (error bars). Asterisk (*) represents a significant difference between conditions

Table 1 Gait parameters and their variability during walking under two conditions, i.e., control condition (CON) and compression stockings condition (CS), mean ± SD

	Step frequency (Hz)	Step length (m)	Step frequency variability (Hz)	Step length variability (m)
CON	1.9515 ± 0.0754	0.6602 ± 0.0254	0.0319 ± 0.0087	0.0134 ± 0.0045
CS	1.9524 ± 0.0797	0.6597 ± 0.0257	0.0351 ± 0.0098	0.0131 ± 0.0041
P value	0.90	0.81	0.09	0.80
Cohen's *d*	0.01	0.02	0.34	0.06

significant difference between conditions for all three joints (p = 0.16–0.85, d = 0.02–0.21).

Discussion

This study aimed to estimate the effects of the compression stockings on metabolic cost and biomechanics during walking. Compression stockings did not lead to a positive consequence for walking economy as expected, but they may have a minor effect on the joint moment while the muscle activation and kinematics were almost unaffected.

Several previous studies have reported that the metabolic cost did not decrease during running or repeated-sprint cycling when wearing compression stockings or full-length lower limb compression tights (Varela-Sanz et al. 2011; Stickford et al. 2015; Brophy-Williams et al. 2019; Broatch et al. 2018). Instead, Bringard et al. (2006)

reported lower energy cost during the running of submaximal intensities when wearing CGs as compared with traditional shorts, and they thought CGs could assist motion patterns by improving proprioception, muscle coordination and propulsive force. By contrast, Dascombe et al. (2011) found that oxygen consumption increased when wearing CGs, and they believed the result may be related to that wearing CGs produced significant resistance to shorten stride length. Given the full-length lower limb compression tights they used, it was possible that the stride length altered though in the current study the step length did not show a significant difference. But the specific reasons for the difference among studies remain unknown. Difference in the exercise intensity and participant population seems not enough to account for the diverse results in energy cost because the exercises involved in the above-mentioned research were of moderate to high intensities and the population of most above-mentioned research was well-trained. All in all, no improvement in energetics for most studies indicates that CGs may have few positive effects on exercise economy. Our result also provides support for the little efficacy of compression stockings in improving the economy and adds to the existing literature about the healthy non-athlete population.

No improvement in the energetics of walking can be partly explained by no improvement in muscle efficiency because generating muscle forces accounts for most of the metabolic cost. Activation of calf muscles kept almost the same pattern and amplitude between CS and CON in this study. To the authors' knowledge, this was the first study to investigate the effects of compression stockings on muscle activation during walking. EMG of most previous studies was reported during maximal voluntary contraction (MVC) after exercises or in isokinetic testing (Miyamoto et al. 2011; Fu et al. 2012; Martorelli et al. 2015; Šambaher et al. 2016), and two other studies investigated the effect on muscle activation during running (Lucas-Cuevas et al. 2017; Kurz and Anders 2018). Muscle activation during MVC decreased or remained unchanged. As suggested by these studies, almost all the motor units were recruited at the beginning of the activity during MVC, and the number of motor units may decrease with the fatigue developing over time. The CGs may have an influence on the fatigue, and thus affect the recruitment of motor units. As for the two running tests, the result showed a lower muscle activation when participants wore CGs. Also of note, Lucas-Cuevas et al. (2017) found that the decrease of muscle activation only appeared in the initial few minutes. They thought this result may be associated with that the pressure applied to the body by the compression stockings decreased gradually over time. If so, this may be one of the reasons for the unchanged muscle activation in our study because we analysed EMG data from the last minute of trials. The other reason may be the exercise intensity. An intense exercise was recommended (Lucas-Cuevas et al. 2017) maybe because it was of large muscle vibration and muscle activation can affect the vibration (Wakeling and Nigg 2001). The effect on muscle activation is less obvious during walking especially for stockings because the calf muscles possess a smaller volume than the thigh muscles. Therefore, in the current study walking may limit the role of compression stockings in improving muscle efficiency.

Wearing compression stockings did not seem to change the kinematics. Most of the previous studies reporting altered kinematics were about jump testing with the compression pressure being exerted to the thigh or the full leg (Wannop et al. 2016; de Britto et al. 2017; Zamporri and Aguinaldo 2018). The kinematics in these studies was mainly estimated using the joint angle. Similarly, Doan et al. (2003) found that hip ROM decreased when wearing compression shorts during 60 metres sprint while several other studies concluded no change in gait parameters when wearing compression stockings during running (Varela-Sanz et al. 2011; Lucas-Cuevas et al. 2015; Stickford et al. 2015). Our study estimated the effects on joint angles and gait parameters together and found no difference between CS and CON. The slight difference of joint angle profile during a gait cycle may result from the change in motor control strategy to adapt to the compression. The difference among studies may lie in the exercise types and CG types. For those exercises of large joint ROM, covering the joint entirely by CGs may produce resistance to the joint movement. Changing the hip angle may be easier than the ankle angle because of a larger ROM of hip relative to the ankle during running and walking. Therefore, it was of no surprise that kinematics did not alter in this study because walking was an exercise of low intensity and the compression stocking used did not cover the ankle joint. Also of note, gait variability did not decrease as expected in this study. By contrast, a previous study examined the effect of CGs on proprioception, where a lower repositioning error was reported when wearing CGs (Ghai et al. 2018). We speculate that the absence of improvement in gait variability in our study may be related to the fact that the participants did not have any experiences of wearing CGs.

Few studies investigated the effect on the joint moments except that Zamporri and Aguinaldo (2018) reported no significant difference in the joint moment during jump testing. In addition, two other studies presented the potential mechanical benefits by calculating the joint torque produced by CGs. Doan et al. (2003) thought that compression shorts could provide amounts of torque at the hip, while Wannop et al. (2016) only found a tendency to increase for hip joint torque produced by CGs. A possible reason for affecting joint torque produced by CGs may lie in the materials. Compression shorts made of neoprene and butyl rubber are much thicker and can provide significant additional elastic force (Doan et al. 2003). Compression stockings used in the current study may not have this characteristic. But this study appeared to confirm the existence of interplay between compression and biological mechanisms which was initially proposed by Kraemer et al. (1996). The increased knee extension moment was compensated by the increased ankle dorsiflexion moment during the early stance phase and the decreased flexion moment was compensated by the decreased ankle plantar flexion moment during the late stance phase. That is, the relative contribution of the knee and ankle to weight support and propulsion altered. Because the ankle joint contributes mostly to the propulsion, the adjustment can lower the burden of the ankle during push-off. Further, it is beneficial to reduce the risk of injuries.

Many studies have investigated the exercise performance, physiological and psychological effects of wearing CGs during various exercises for athletes and recreational individuals. The reasons for showing different results among studies are diverse, such as the exercise types, CG types and levels of pressure. The placebo effect can also partly account for the difference. Using the condition of wearing nothing as a control condition will inevitably introduce the placebo effect while using traditional tights or stockings as a control condition can minimize the effect. Also of note, inter-individual differences are also common in previous studies (Stickford et al. 2015; Treseler et al. 2016), which may result from the difference of physical conditions and psychological effects.

There existed some limitations in the current study. One was the asynchronous measurement of kinematic and kinetic data due to the limitation of the experimental condition. Although we tried to make the control variables of treadmill walking trials be consistent with those of the force plate walking trials, the difference was still obvious especially for walking speed. However, whether for treadmill walking or the force plate walking step frequency and walking speed did not show a significant difference between CS condition and CON condition, so we thought that the conclusion was almost unaffected. The other limitation was that we did not measure the actual pressure. To differentiate the two conditions from each other more obviously, the range of pressure that we chose was relatively large. But this resulted in that the pressure exerted on the wearer was larger than that Ali et al. (2011) reported was the most comfortable (12–15 mmHg). As Rider et al. speculated, the comfort may have an influence on the result (Rider et al. 2014).

This study adds to the literature about the biomechanical effect of compression stockings during walking. Unlike most previous studies, we did not choose athletes to participate in the experiment, and participants in our study had never worn CGs before the experiment according to their self-reports. Whether or not the participants are athletes may have an effect on the result. In fact, changing the habitual movement pattern may be more difficult for athletes than for non-athletes (Stickford et al. 2015). As discussed above, compression stockings may not be recommended for improving economy and muscle efficiency during walking for non-athletes who do not have any experiences of wearing CGs. If the kinematics is not expected to be changed, the kind of CGs not covering the joint entirely may be more appropriate. In addition, it may play a minor role in improving the joint kinetics, and thus avoiding injuries. Future study regarding biomechanics can avoid limitations of this study to maximize the potential biomechanical benefits.

Conclusions

Our results suggest that compression stockings have trivial effects on the metabolic cost, kinematics and muscle activation for most participants, and only a few participants may have the metabolic benefit. The joint kinetics does become adjusted as a consequence of the pressure exerted by compression stockings. And the adjustment is of benefit to lowering the burden of ankle joint during propulsion. Further success can be achieved by making the best of the physiological and mechanical benefits as well as the potential interplay between compression garments and biomechanics.

Acknowledgements The authors would like to acknowledge all participants who volunteered to participate in the experiment. We also would like to render thanks to Di Hu, Yuyao Liu, Bo Huang, Xiaowei Xu, Chuang Liu and Zhiliang Xie for all their advice.

Author contributions CX conceived and designed research. LC conducted experiments, analyzed data and wrote the manuscript. CX revised the manuscript. All authors read and approved the manuscript.

Funding This work was supported by the National Natural Science Foundation of China under Grants 91648203, and Program of International Science and Technology Cooperation of China under Grant 2016YFE0113600.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Agu O, Baker D, Seifalian AM (2004) Effect of graduated compression stockings on limb oxygenation and venous function during exercise in patients with venous insufficiency. Vascular 12(1):69–76. https://doi.org/10.1258/rsmvasc.12.1.69

Ali A, Creasy RH, Edge JA (2010) Physiological effects of wearing graduated compression stockings during running. Eur J

Appl Physiol 109(6):1017–1025. https://doi.org/10.1007/s00421-010-1447-1
Ali A, Creasy RH, Edge JA (2011) The effect of graduated compression stockings on running performance. J Strength Cond Res 25(5):1385–1392. https://doi.org/10.1519/JSC.0b013e3181d6848e
Areces F, Salinero JJ, Abian-Vicen J, González-Millán C, Ruiz-Vicente D, Lara B, Lledó M, Del Coso J (2015) The use of compression stockings during a marathon competition to reduce exercise-induced muscle damage: are they really useful? J Orthop Sports Phys Ther 45(6):462–470
Bartlett R (1999) Sports biomechanics: reducing injury and improving performance. Routledge
Barwood MJ, Corbett J, Feeney J, Hannaford P, Henderson D, Jones I, Kirke J (2013) Compression garments: no enhancement of high-intensity exercise in hot radiant conditions. Int J Sports Physiol Perform 8(5):527–535. https://doi.org/10.1123/ijspp.8.5.527
Bringard A, Perrey S, Belluye N (2006) Aerobic energy cost and sensation responses during submaximal running exercise-positive effects of wearing compression tights. Int J Sports Med 27(05):373–378
Broatch JR, Bishop DJ, Halson S (2018) Lower limb sports compression garments improve muscle blood flow and exercise performance during repeated-sprint cycling. Int J Sports Physiol Perform 13(7):882–890. https://doi.org/10.1123/ijspp.2017-0638
Brockway J (1987) Derivation of formulae used to calculate energy expenditure in man. Hum Nutr Clin Nutr 41(6):463–471
Brophy-Williams N, Driller MW, Kitic CM, Fell JW, Halson SL (2017) Effect of compression socks worn between repeated maximal running bouts. Int J Sports Physiol Perform 12(5):621–627. https://doi.org/10.1123/ijspp.2016-0162
Brophy-Williams N, Driller MW, Kitic CM, Fell JW, Halson SL (2019) Wearing compression socks during exercise aids subsequent performance. J Sci Med Sport 22(1):123–127. https://doi.org/10.1016/j.jsams.2018.06.010
Chatard J (1998) Elastic bandages, recovery and sport performance. Health Protective Text 2:79–84
Collins SH, Wiggin MB, Sawicki GS (2015) Reducing the energy cost of human walking using an unpowered exoskeleton. Nature 522(7555):212–215. https://doi.org/10.1038/nature14288
Conley DL, Krahenbuhl GS (1980) Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 12(5):357–360
Dascombe BJ, Hoare TK, Sear JA, Reaburn PR, Scanlan AT (2011) The effects of wearing undersized lower-body compression garments on endurance running performance. Int J Sports Physiol Perform 6(2):160–173
de Britto MA, Lemos AL, dos Santos CS, Stefanyshyn DJ, Carpes FP (2017) Effect of a compressive garment on kinematics of jump-landing tasks. J Strength Cond Res 31(9):2480–2488. https://doi.org/10.1519/JSC.0000000000001620
De Luca CJ (1997) The use of surface electromyography in biomechanics. J Appl Biomech 13(2):135–163
Dean JC (1985) Kuo AD (2011) Energetic costs of producing muscle work and force in a cyclical human bouncing task. J Appl Physiol 110(4):873–880. https://doi.org/10.1152/japplphysiol.00505.2010
Del Coso J, Areces F, Salinero JJ, González-Millán C, Abián-Vicén J, Soriano L, Ruiz D, Gallo C, Lara B, Calleja-Gonzalez J (2014) Compression stockings do not improve muscular performance during a half-ironman triathlon race. Eur J Appl Physiol 114(3):587–595
Doan B, Kwon Y-H, Newton R, Shim J, Popper E, Rogers R, Bolt L, Robertson M, Kraemer W (2003) Evaluation of a lower-body compression garment. J Sports Sci 21(8):601–610. https://doi.org/10.1080/0264041031000101971
Driller MW, Halson SL (2013) The effects of wearing lower body compression garments during a cycling performance test. Int J Sports Physiol Perform 8(3):300–306
Duffield R, Portus M (2007) Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players. Br J Sports Med 41(7):409–414. https://doi.org/10.1136/bjsm.2006.033753
Fu W, Liu Y, Zhang S, Xiong X, Wei S (2012) Effects of local elastic compression on muscle strength, electromyographic, and mechanomyographic responses in the lower extremity. J Electromyogr Kinesiol 22(1):44–50. https://doi.org/10.1016/j.jelekin.2011.10.005
Ghai S, Driller MW, Masters RS (2018) The influence of below-knee compression garments on knee-joint proprioception. Gait Posture 60:258–261. https://doi.org/10.1016/j.gaitpost.2016.08.008
Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G (1999) European recommendations for surface electromyography. Roessingh Res Develop 8(2):13–54
Ibegbuna V, Delis KT, Nicolaides AN, Aina O (2003) Effect of elastic compression stockings on venous hemodynamics during walking. J Vasc Surg 37(2):420–425. https://doi.org/10.1067/mva.2003.104
Jakeman JR, Byrne C, Eston RG (2010) Lower limb compression garment improves recovery from exercise-induced muscle damage in young, active females. Eur J Appl Physiol 109(6):1137–1144. https://doi.org/10.1007/s00421-010-1464-0
Kang J, Chaloupka EC, Mastrangelo AM, Hoffman JR (2002) Physiological and biomechanical analysis of treadmill walking up various gradients in men and women. Eur J Appl Physiol 86(6):503–508. https://doi.org/10.1007/s00421-002-0583-7
Kemmler W, von Stengel S, Köckritz C, Mayhew J, Wassermann A, Zapf J (2009) Effect of compression stockings on running performance in men runners. J Strength Cond Res 23(1):101–105. https://doi.org/10.1519/JSC.0b013e31818eaef3
Kepple TM, Siegel KL, Stanhope SJ (1997) Relative contributions of the lower extremity joint moments to forward progression and support during gait. Gait Posture 6(1):1–8
Kraemer WJ, Bush JA, Bauer JA, Tripleft-McBride N, Paxton NJ, Clemson A, Koziris LP, Mangino LC, Fry AC, Newton RU (1996) Influence of compression garments on vertical jump performance in NCAA Division I volleyball players. J Strength Cond Res 10:180–183
Kurz E, Anders C (2018) Effects of wearing lower leg compression sleeves on locomotion economy. J Sports Sci 36(18):1–6. https://doi.org/10.1080/02640414.2018.1439355
Lucas-Cuevas A, Priego-Quesada J, Aparicio I, Giménez J, Llana-Belloch S, Pérez-Soriano P (2015) Effect of 3 weeks use of compression garments on stride and impact shock during a fatiguing run. Int J Sports Med 94(10):826–831. https://doi.org/10.1055/s-0035-1548813
Lucas-Cuevas ÁG, Priego Quesada JI, Giménez JV, Aparicio I, Cortell-Tormo JM, Pérez-Soriano P (2017) Can graduated compressive stockings reduce muscle activity during running? Res Q Exerc Sport 88(2):223–229
Martorelli SS, Martorelli AS, Pereira MC, Rocha-Junior VA, Tan JG, Alvarenga JG, Brown LE, Bottaro M (2015) Graduated compression sleeves: effects on metabolic removal and neuromuscular performance. J Strength Cond Res 29(5):1273–1278. https://doi.org/10.1519/JSC.0000000000000401
Miyamoto N, Hirata K, Mitsukawa N, Yanai T, Kawakami Y (2011) Effect of pressure intensity of graduated elastic compression stocking on muscle fatigue following calf-raise exercise. J Electromyogr Kinesiol 21(2):249–254. https://doi.org/10.1016/j.jelekin.2010.08.006
Mündermann A, Nigg BM, Humble RN, Stefanyshyn DJ (2003) Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. Med Sci Sports Exerc 35(10):1710–1719

Orizio C (1992) Soundmyogram and EMG cross-spectrum during exhausting isometric contractions in humans. J Electromyogr Kinesiol 2(3):141–149

Rider BC, Coughlin AM, Hew-Butler TD, Goslin BR (2014) Effect of compression stockings on physiological responses and running performance in division III collegiate cross-country runners during a maximal treadmill test. J Strength Cond Res 28(6):1732–1738. https://doi.org/10.1519/JSC.0000000000000287

Šambaher N, Aboodarda SJ, Silvey DB, Button DC, Behm DG (2016) Effect of an ankle compression garment on fatigue and performance. J Strength Cond Res 30(2):326–335. https://doi.org/10.1519/Jsc.0000000000001011

Selinger JC, O'Connor SM, Wong JD, Donelan JM (2015) Humans can continuously optimize energetic cost during walking. Curr Biol 25(18):2452–2456. https://doi.org/10.1016/j.cub.2015.08.016

Stickford AS, Chapman RF, Johnston JD, Stager JM (2015) Lower-leg compression, running mechanics, and economy in trained distance runners. Int J Sports Physiol Perform 10(1):76–83. https://doi.org/10.1123/ijspp.2014-0003

Tarata MT (2003) Mechanomyography versus Electromyography, in monitoring the muscular fatigue. BioMed Eng Online 2(1):3. https://doi.org/10.1186/1475-925x-2-3

Treseler C, Bixby WR, Nepocatych S (2016) The effect of compression stockings on physiological and psychological responses after 5-km performance in recreationally active females. J Strength Cond Res 30(7):1985–1991

Varela-Sanz A, España J, Carr N, Boullosa DA, Esteve-Lanao J (2011) Effects of gradual-elastic compression stockings on running economy, kinematics, and performance in runners. J Strength Cond Res 25(10):2902–2910. https://doi.org/10.1519/JSC.0b013e31820f5049

Voloshina AS, Ferris DP (2015) Biomechanics and energetics of running on uneven terrain. J Exp Biol 218(5):711–719

Wakeling JM, Nigg BM (2001) Modification of soft tissue vibrations in the leg by muscular activity. J Appl Physiol 90(2):412–420

Wannop JW, Worobets JT, Madden R, Stefanyshyn DJ (2016) Influence of compression and stiffness apparel on vertical jump performance. J Strength Cond Res 30(4):1093–1101

Zamporri J, Aguinaldo A (2018) The effects of a compression garment on lower body kinematics and kinetics during a drop vertical jump in female collegiate athletes. Orthopaed J Sports Med 6(8):2325967118789955. https://doi.org/10.1177/2325967118789955

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.