Acta of Bioengineering and Biomechanics
Vol. 17, No. 4, 2015

Original paper
DOI: 10.5277/ABB-00155-2014-06

The muscle activation patterns of lower limb during stair climbing at different backpack load

HAN YALI[1, 2]*, SONG AIGUO[1], GAO HAITAO[2], ZHU SONGQING[2]

[1] School of Instrument Science and Engineering, Southeast University, Nanjing, China.
[2] School of Mechanical Engineering, Nanjing Institute Of Technology, Nanjing, China.

Stair climbing under backpack load condition is a challenging task. Understanding muscle activation patterns of lower limb during stair climbing with load furthers our understanding of the factors involved in joint pathology and the effects of treatment. At the same time, stair climbing under backpack load requires adjustments of muscle activations and increases joint moment compared to level walking, which with muscle activation patterns are altered as a result of using an assistive technology, such as a wearable exoskeleton leg for human walking power augmentation. Therefore, the aim of this study was to analyze lower limb muscles during stair climbing under different backpack load. Nine healthy volunteers ascended a four-step staircase at different backpack load (0 kg, 10 kg, 20 kg, 30 kg). Electromyographic (EMG) signals were recorded from four lower limb muscles (gastrocnemius, tibialis anterior, hamstring, rectus femoris). The results showed that muscle activation amplitudes of lower limb increase with increasing load during stair climbing, the maximum RMS of gastrocnemius are greater than tibialis anterior, hamstring and rectus femoris whether stair climbing or level walking under the same load condition. However, the maximum RMS of hamstring are smaller than gastrocnemius, tibialis anterior and rectus femoris. The study of muscle activation under different backpack load during stair climbing can be used to design biomechanism and explore intelligent control based on EMG for a wearable exoskeleton leg for human walking power augmentation.

Key words: *stair climbing, backpack load, muscle activation pattern, surface electromyography*

1. Introduction

Stair climbing is a common activity of daily living, yet it is a strenuous task especially in the case of backpack load. Today, although elevator is mainly used for stair climbing, stair climbing with backpack load is still commonly encountered in the workplace, home and community. Several investigations have furthered our understanding of the lower limb function in stair climbing [1], [4], [5], [7], [19]. These studies outlined the joint kinetics and demonstrated that the magnitudes of the flexion-extension moments at the hip and knee are greater during stair climbing than during level walking. Recently, some researchers examined the influence of step height [16], gait velocity [17], age [12] and staircase inclinations [14] on lower limb biomechanics. Some studies also investigated changes in patients with knee and hip implants [2], [3], amputees with artificial limbs [13] or athletes with anterior cruciate ligament deficiencies [9].

However, no comprehensive analysis is available in the literature that would discuss the lower limb biomechanics effects of increased backpack load during stair climbing. Electromyographic (EMG) activity patterns have been used to provide insight into neural control strategies for different locomotor tasks in human motion [1], [15], [18]. Lower limb EMG activity for stair climbing in humans has been reported only sporadically and not in the context of backpack load condition [1], [16]. The extra ground reaction forces applied to elevate the body require an increase in the overall support moment with the load increase during stair climbing, but this moment could be distributed differently among the hip, knee and ankle joint of lower limb. To better understand the complex relation

* Corresponding author: Han Yali, School of Mechanical Engineering, Nanjing Institute of Technology, Nanjing 211167, China. Tel:+862552113597, e-mail: s966237@163.com

Received: August 9th, 2014
Accepted for publication: December 18th, 2014

between muscle fascicle behavior and joint biomechanics in stair climbing at backpack load, we examine the effects of backpack load on the muscle behavior of lower limb.

2. Materials and method

2.1. Subjects

Ten college students (males) of similar body height (1.7 ± 0.03 m), weight (57 ± 6.5 kg) and age (25 ± 2 years) partipated in the measurements. All subjects gave their informed consent for the study. All of them were healthy, free from gait impairment or any musculo-skeletal or neurological dysfunction.

2.2. Staircase design

The staircase (rise = 170 mm, tread = 270 mm, width = 400 mm) was designed taking into consideration the walking safety and comfort ability. It was composed of three steps, as shown in Figs. 1 and 2. The lower three steps were instrumented with force plates each, the upper landing was used to stand after each trial. Each step in the staircase as well as the upper landing was constructed separately enabling forces to be recorded independently from each step. The ground reaction force, the ground reaction moment and the location of the center of pressure were outputted by Motion Analysis system. No handrails were necessary because all participants were capable of ascending the staircase used in this study without using them.

Fig. 1. Photograph of experiment scene

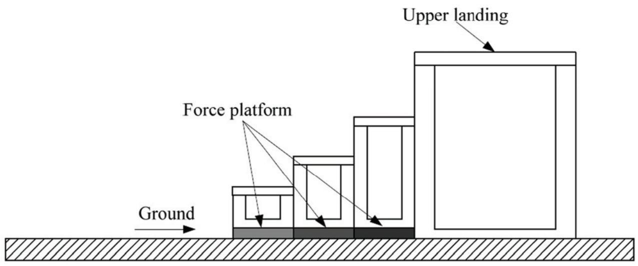

Fig. 2. Schematic drawing of staircase with upper landing

2.3. Measurement of electromyographic activity

Electromyography (EMG) activity was measured on the left and right leg from four muscles, assumed to be representative of the major hip, knee and ankle joint extensors and flexors: gastrocnemius, tibialis anterior, medial hamstring and rectus femoris. Before electrode placement, we prepared the shaved skin of the leg with fine sandpaper and alcohol. Disposable Ag-AgC1 electrodes with a circular uptake area of 1 cm in diameter and an inter electrode distance of 2 cm were used. They were placed on the skin overlying the approximate electromyogram being observed, and electrode position and signal quality were verified using an oscilloscope while having participants contract the instrumented muscles. The electrode pair was relocated if an inadequate recording or crosstalk occurred. The interelectrode distance was 2 cm. An EMG system (MotionLabs Corp.) was used and encompassed one very lightweight trailing cable from the subject to the main unit. The EMG signals were synchronised with the kinematics and kinematic data (Motion Analysis Corp.) by using an external trigger to start both the EMG and vision system data capture simultaneously. EMG signals were recorded at 1200 Hz. Raw SEMG was centered and high-pass filtered (4th-order Butterworth filter, 100 Hz), and a root mean square (RMS) of the SEMG was calculated subsequently using Matlab.

2.4. Protocol

All participants were given the instruction to walk barefoot at their normal comfortable speed, to use their right leg for the first step, to only place one foot on each step (foot-over-foot ascent), and to continue walking in a straight line reaching the upper landing. A stride cycle was defined starting with foot contact on the first step and ending at the next foot contact on the third step during ascent. Prior to data acquisition, the subjects ascended the stairs several times until they were accustomed to the motion. For each subject and for each backpack load, ascending movements were recorded for three repetitive trails. Any trials with visible hesitation, misplaced footing, or stumbles were excluded from further analysis.

For comparison with level walking data, all participants were requested to walk on a level with backpack load. Two force plates were embedded in the floor. The force plates, developed by Advanced Mechanical Technology Incorporated (AMTI), feature a loading range of up to 500 N and a size of 0.51 m × 0.46 m × 0.08 m. The subject began with the condition to habituate himself to the walkway area, and then performed three walking trials under each backpack load condition with almost the same speed, during which his two feet made contact on two embedded force platforms separately. The subjects used their right leg for the first step, and the left leg for the second step. Before each trial, the subjects rested for 5 min for reducing fatigue effect.

2.5. Data analysis

From every trial, the stride cycle between the first touchdown of the right foot (on the first step) and the second touchdown of the right foot (two steps above) was analyzed. The kinematics data were captured at 60 Hz using a camera 3D optical capture system (Motion Analysis Corp.). The three-dimensional coordinates of three non-collinear infrared markers, placed on the feet (lateral heel, dorsum, 5th metatarsal head), legs (lateral malleolus, mid-shank, fibula head), thighs (greater trochanter, mid-thigh, lateral femoral condyle), pelvis (left and right posterior superior iliac spines, left iliac crest) and trunk were acquired during the level and stair climbing tasks. The relative angles were calculated using rotation matrices arranged in a Cardan ($x - y - z$ rotation) sequence such that the local x, y and z axes corresponded respectively to abduction-adduction, rotation and flexion-extension for the hip and knee joints, and eversion-inversion, rotation, and dorsiflexion, plantar flexion at the ankle joint.

The ground reaction forces (kinetic data) were collected at 1200 Hz. The three-dimensional coordinates of makers and ground reaction forces were synchronized. The net moments at the ankle, knee and hip joints were calculated according to the methods of Vaughan et al. [20]. Then, the net muscle power at each joint was computed by multiplying the joint angular velocity by the local net muscle moment within each plane of movement. All kinematics and kinetic data were time-normalized to 100 points over the stride. The values for each point of interest were taken from all trials and averaged within subjects. Statistical analyses were done using SPSS software. Only the sagittal plane information was further analyzed.

3. Results

3.1. Muscle activity

The muscle activation patterns during stair climbing under different backpack load are shown in Figs. 3 through 6. The tibialis anterior is active from late stance through swing phase, as shown in Fig. 3. The gastrocnemius is active throughout most of the stance phase, especially, the intensity of the activity is maximum during the procedure of toe-off, as shown in Fig. 4. The rectus femoris is active from heel strike through midstance, as shown in Fig. 5. The hamstring is active throughout most of the stance phase, and is also active during the latter part of swing, as shown in Fig. 6.

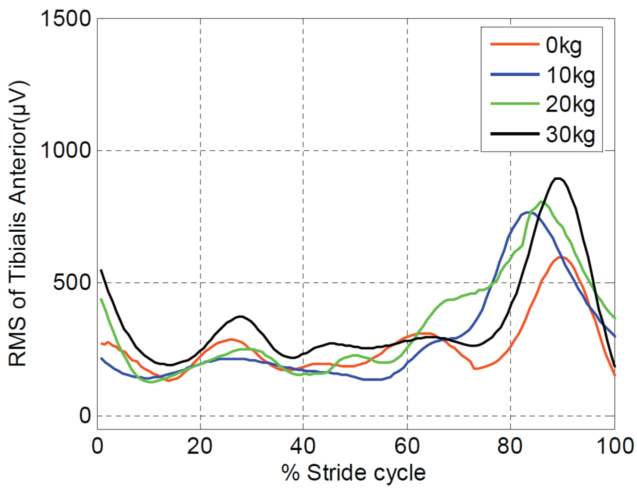

Fig. 3. Root mean square (RMS) of the tibialis anterior SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during stair climbing, stride cycle begins from the heel strike, stance phase, toe-off (about 76%), swing phase, and ends next heel strike

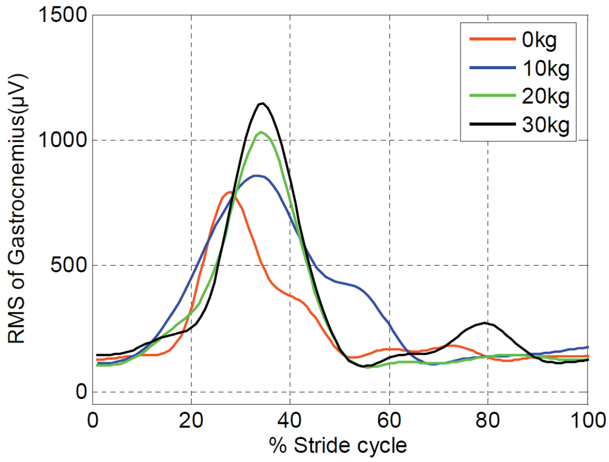

Fig. 4. Root mean square (RMS) of the gastrocnemius SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during stair climbing, stride cycle begins from the heel strike, stance phase, toe-off (about 76%), swing phase, and ends next heel strike

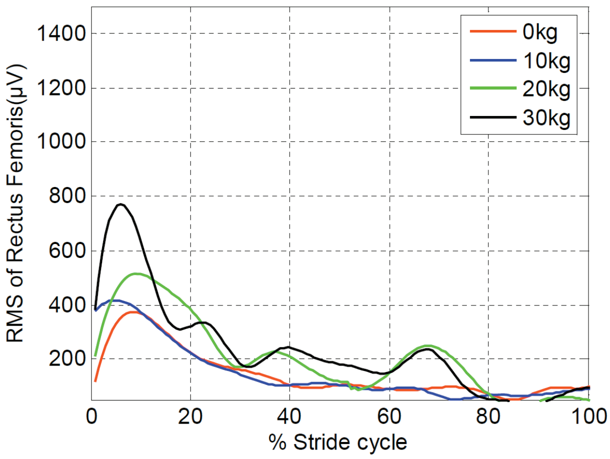

Fig. 5. Root mean square (RMS) of the rectus femoris SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during stair climbing, stride cycle begins from the heel strike, stance phase, toe-off (about 76%), swing phase, and ends next heel strike

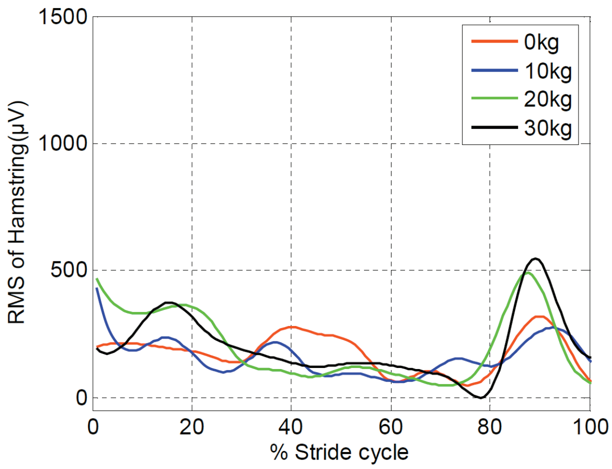

Fig. 6. Root mean square (RMS) of the hamstring SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during stair climbing, stride cycle begins from the heel strike, stance phase, toe-off (about 76%), swing phase, and ends next heel strike

The muscle activation patterns during level walking under different backpack load are shown in Figs. 7 through 10. The tibialis anterior is active from the end of stance through swing to the beginning of the next stance phase, as shown in Fig. 7. The gastrocnemius is active during stance phase, especially, the duration of single leg support, as shown in Fig. 8. The rectus femoris is active around heel strike, and also being active throughout most of the stance phase with increasing load, as shown in Fig. 9. The hamstring is active during the period of the stance to swing transition, as shown in Fig. 10.

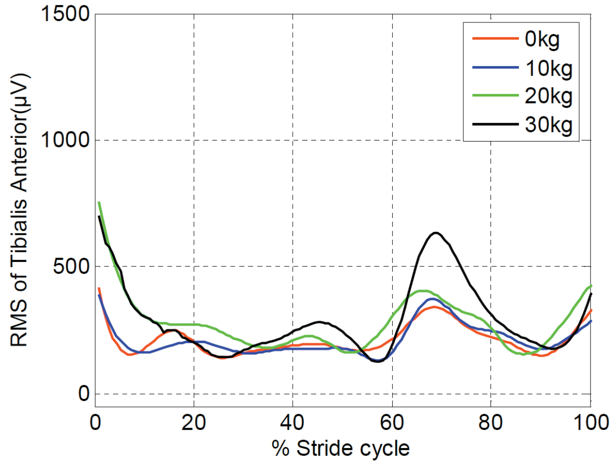

Fig. 7. Root mean square (RMS) of the Tibialis anterior SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during level walking, stride cycle begins from the heel strike, stance phase, toe-off (about 64%), swing phase, and ends next heel strike

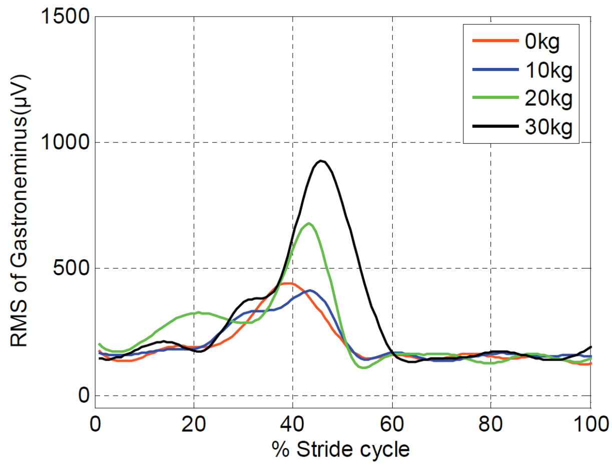

Fig. 8. Root mean square (RMS) of the gastrocnemius SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during level walking, stride cycle begins from the heel strike, stance phase, toe-off (about 64%), swing phase, and ends next heel strike

The muscle activation amplitudes of lower limb increase with increasing load during stair and level walking. The RMS of gastrocnemius, tibialis anterior, hamstring and rectus femoris are significantly greater with the maximum loads compared with the no-load condition, and the RMS of gastrocnemius, tibialis anterior, hamstring and rectus femoris are generally greater during the stair climbing compared to the level walking under the same load condition. The maximum RMS of gastrocnemius are greater than tibialis anterior, hamstring and rectus femoris whether stair climbing or level walking under the same load condition. However, the maximum RMS of hamstring is smaller than gastrocnemius, tibialis anterior and rectus femoris.

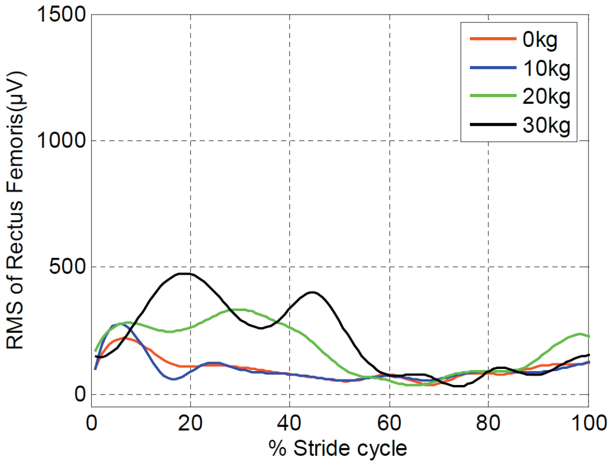

Fig. 9. Root mean square (RMS) of the rectus femoris SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during level walking, stride cycle begins from the heel strike, stance phase, toe-off (about 64%), swing phase, and ends next heel strike

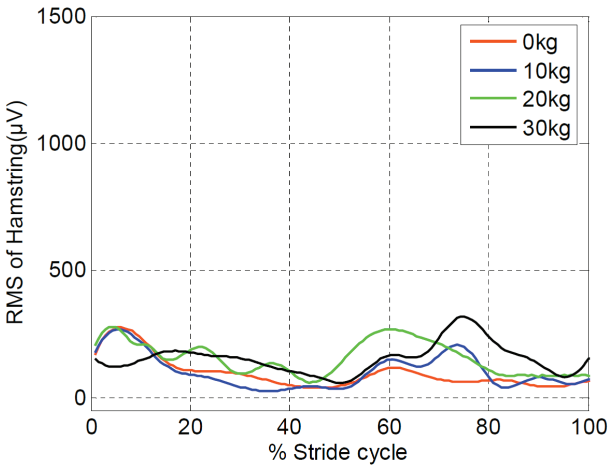

Fig. 10. Root mean square (RMS) of the hamstring SEMG curves for the bakpack load of 0 kg, 10 kg, 20 kg and 30 kg during level walking, stride cycle begins from the heel strike, stance phase, toe-off (about 64%), swing phase, and ends next heel strike

3.2. Kinematics and kinetics

Table 1 gives the stride parameters during different walking conditions. The stride time increased with increasing load during stair climbing and level walking. The stance phase was between 75.5 and 76.8% of the stride duration during stair climbing, and the stance phase was between 63 and 64.6% of the stride duration during level walking. Differences were observed in the stance phase. They are significantly longer during stair climbing than level walking.

Table 1. Comparison of stair climbing and level walking stride time (average value and deviation value)

Type of walking	Mass of load (kg)	Stance time (s) Avg. (SD)	Stride time (s) Avg. (SD)
Stair climbing	0 kg	1.08 (0.01)	1.43 (0.01)
	10 kg	1.09 (0.01)	1.44 (0.01)
	20 kg	1.12 (0.01)	1.46 (0.01)
	30 kg	1.13 (0.02)	1.47 (0.02)
Level walking	0 kg	0.70(0.01)	1.11 (0.01)
	10 kg	0.71 (0.01)	1.12 (0.01)
	20 kg	0.74 (0.01)	1.15 (0.01)
	30 kg	0.75 (0.01)	1.16 (0.01)

The joint angular displacements during different walking conditions are shown in Figs. 11–13. At foot contact of stair climbing, the ankle is plantar flexed and the knee and hip are flexed. As the lower limb moves from foot-strike to mid-stance during stair climbing, the ankle is dorsiflexed slightly and the knee and hip extend. The ankle was dorsiflexed and attained a maximal value around the transition to single support, the knee and hip nearly fully extended as the lower limb moves from mid-stance to toe-off. At the swing phase of stair climbing, the knee and hip are flexed and knee attains maximum flexion about at the mid-swing. From mid-swing to another foot-strike during stair climbing, the knee and hip move from a position of maximum flexion toward extension, while the ankle joint moves from a position of maximum dorsiflexion toward plantar flexion.

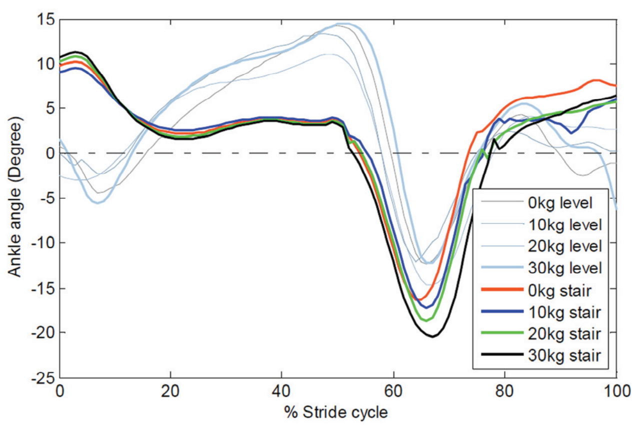

Fig. 11. Angles of ankle joint in different walking conditions

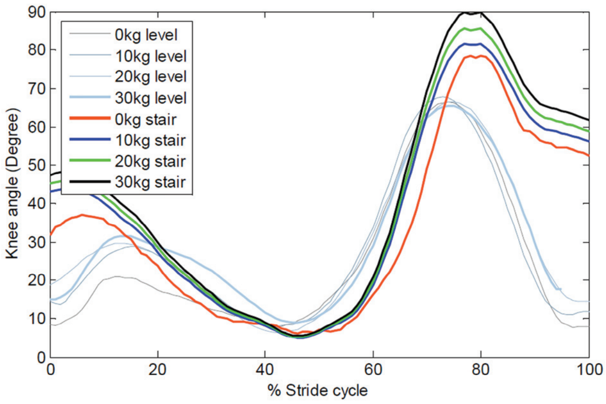

Fig. 12. Angles of knee joint in different walking conditions

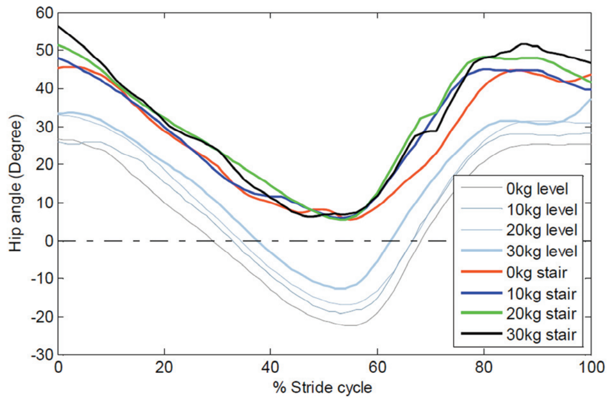

Fig. 13. Angles of hip joint in different walking conditions

Considerable differences were observed when comparing joint angles during stair climbing and level walking, which is in agreement with previous studies [12]. The angular ranges were generally larger during stair climbing than level walking. Notably, in stair climbing, a large flexion at the knee was observed at the beginning of the stance phase and the middle of the swing phase during stair climbing than level walking. Although hip profiles were similar between stair climbing and level walking, a more flexed position at the hip was observed during stair climbing. The joint ranges and maximum flexion angles increased with increasing load during stair climbing, but there was no significant increase with backpack load increasing.

The maximum of joint moments during different walking conditions are shown in Fig. 14, Fig. 15 and Table 2. Joint moments are more dependent on backpack load than joint angles. Absolute joint moment maximums increased with increasing backpack load during stair climbing and level walking. The maximum moment values of knee increase more than ankle and hip joint during stair climbing, for example, the peak knee moment increased 30.9% at the 10 kg load, 78.8% at 20 kg and 92.9% at 30 kg compared to the peak moment at 0 kg load, respectively. However, the peak ankle moment increased 14.7% at 10 kg load, 29.5% at 20 kg and 55.6% at 30 kg compared to the peak moment at 0 kg load (Table 2). Considerable differences are also observed in that the maximum moment values of ankle and knee are generally larger during stair climbing than during level walking, but the maximum moment values of hip are generally smaller than level walking.

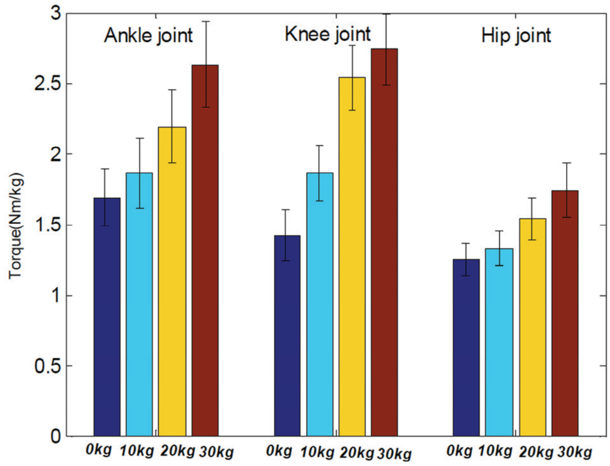

Fig. 14. Joint torques during stair climbing

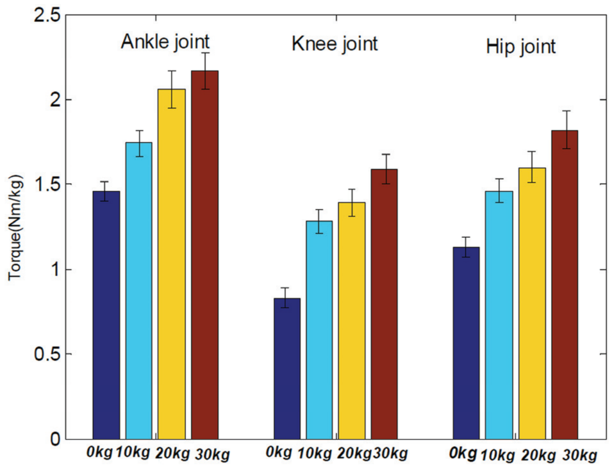

Fig. 15. Joint torques during level walking

Table 2. Comparison of stair climbing and level walking joint peak torque (average value and deviation value)

Type of walking	Mass of load (kg)	Ankle peak torque (Nm/kg)	Knee peak torque (Nm/kg)	Hip peak torque (Nm/kg)
Stair climbing	0 kg	1.69(0.20)	1.42(0.18)	1.25(0.11)
	10 kg	1.94(0.25)	1.86(0.20)	1.33(0.12)
	20 kg	2.19(0.26)	2.54(0.23)	1.54(0.15)
	30 kg	2.63(0.30)	2.74(0.25)	1.74(0.19)
Level walking	0 kg	1.46(0.06)	0.83(0.06)	1.13(0.06)
	10 kg	1.74(0.08)	1.28(0.07)	1.46(0.07)
	20 kg	2.06(0.11)	1.39(0.08)	1.60(0.09)
	30 kg	2.17(0.11)	1.59(0.09)	1.82(0.11)

4. Discussion

4.1. Muscle activity

The goal of this study was to determine which muscle activation and what stage activation with load increase during stair climbing and level walking. In achieving this goal, we provide a comprehensive description of lower extremity muscle activation, kinematics and kinetics with backpack load 0 kg, 10 kg, 20 kg and 30 kg. The muscle activity patterns in Figs. 3–6 showed that the tibialis anterior is active from late stance through swing phase, to make sure foot raise the next staircase and land suitable placement. The gastrocnemius, rectus femoris and hamstrings are active throughout most of the stance phase in an extensor synergy for lifting and support. In summary, the main phase of muscle activity takes place at the push-up phase during stair climbing, where the RMS magnitudes are greater than other phase.

There are many differences in the activities of the muscles during stair climbing as opposed to level walking. These differences in activity are mainly in the muscles responsible for vertical movement of the body. Climbing up stairs, the differences are reflected by changes in the contractions of the rectus femoris, hamstrings, tibialis anterior and gastrocneminus during the support phase.

Individual muscles contribute differently to load mass. Gastrocneminus and tibialis anterior are the muscles with the two largest physiological cross-sectional areas in the lower limb and their activations increase significantly with load increase, thus, they likely contribute substantially to load changes during stair climbing and level walking. Especially, the gastrocneminus, the maximum RMS of gastrocnemius are greater than tibialis anterior, hamstring and rectus femoris whether stair climbing or level walking under the same load condition. However, the maximum RMS of hamstring is smaller than gastrocnemius, tibialis anterior and rectus femoris.

A fundamental consideration, already pointed out in the work of McFadyen and Winter [10] is that the ascending task consists primarily of a transfer of muscle energy into potential (gravitation) energy of the body. Our experiment results also showed that muscle activity generally increased with backpack load increasing, the RMS of gastrocnemius, tibialis anterior, hamstring and rectus femoris are significantly greater with the maximum loads compared to the no-load condition.

4.2. Kinematics and kinetics

Table 1 showed that the stride time increased with increasing load during stair climbing and level walking. The explanation for this prolonged stance phase might come from the requirement to maintain good body balance. The load carried on the back raised the center of gravity of the locomotor system, thus diminishing the stability of equilibrium. The subjects were forced to adjust their gait to compensate for this change by lengthening the stance duration (or reducing the swing duration) [6], [8].

The joint angular displacements during stair climbing are similar to those reported by Nadeau and Riener et al. [12], [14]. In comparison to level walking, the lower limbs were observed to be more flexed at the beginning of the foot strike and less extension at the hip was observed at toe-off. These observations reflected specific adaptations to the staircase environment. The knee and hip need to be flexed at foot contact to place the leg on the step. At the end of the stance phase of stair climbing, the hips do not need to extend as much as in level walking because the contralateral step length is reduced by the geometry of the staircase, as opposed to level walking where there is no such constraint. As supported by previous studies [14], these differences in the range of motion between stair climbing and level walking may depend of the staircase configuration and subject characteristics. The angular displacements at the hip and knee were similar to those reported in studies using two-dimensional analyses [11].

Stair climbing is characterised by large moments and powers produced in the sagittal plane as previously shown [10], [14]. A considerable portion of these moments and powers are required to support and propel the body against gravity and to generate movements that advance the body forward in the plane of progression like in level walking. In addition, stair climbing required raising the body while progressing to the next step; the main task that is very demanding for the lower limb muscles as shown by the large increase in the moments and powers in stair climbing in comparison with level walking. Mechanically, this essential task is performed by the extensor muscles of the lower limb. Particularly, the knee extension moment is doubled in comparison to level walking. This strong action of the knee extensors in stair climbing was also shown by EMG studies that revealed high and prolonged activities of the vastus medialis and rectus femoris during the first part of the stance phase.

5. Conclusion

The analyses of lower limb muscles under different backpack load during stair climbing revealed that substantial amounts of effort are required in the frontal plane, because of stair climbing with backpack load required a reorganization of the ower limb muscular activation pattern in order to respond to additional mechanical requirements such as rising the human body and backpack load to the next step and avoiding the intermediate step. Therefore, there are major differences in patterns between stair climbing and level walking. Gastrocneminus activations increase significantly with load increase, but the maximum RMS of hamstring is smaller than rectus femoris, tibialis anterior and gastrocneminus under the same load condition. The stair climbing is characterized by larger moments and powers produced in comparison to level walking, these moments and powers are required to support and propel the body against gravity and to generate movements that advance the body forward, so the more demanding for the lower limb muscles in stair climbing, which is the reason for more activities of muscles during stair climbing as opposed to level walking. These results can be used to design biomechanism and explore intelligent control based on EMG for a wearable exoskeleton leg for human walking power augmentation.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 51205182) and Natural Science Foundation of Jiangsu Province of China (Grant No. BK2012474).

References

[1] ANDRIACCHI T.P., ANDERSSON G.B.J., FERMIER R.W., STERN D., GALANTE J.O., *A study of lower-limb mechanics during stair-climbing*, J, Bone Joint Surg,, 1980, Vol. 62, 749–757.

[2] ANDRIACCHI T.P., GALANTE J.O., FERMIER R.W., *The influence of total knee-replacement design on walking and stair climbing*, J, Bone Joint Surg,, 1982, Vol. 64, 1328–1335.

[3] BERGMANN G., GRAICHEN F., ROHLMANN A., *Is staircase walking a risk for the fixation of hip implants?* J, Biomech,, 1995, Vol. 5, 535–553.

[4] BLAZKIEWICZ M., *Muscle force distribution during forward and backward locomotion*, Acta Bioeng. Biomech., 2013, Vol. 15(3), 3–9.

[5] COSTIGAN P.A., DELUZIO K.J., WYSS U.P., *Knee and hip kinetics during normal stair climbing*, Gait and Posture, 2006, Vol. 16, 31–37.

[6] FINCH L., BARBEAU H., ARSENAULT B., *Influence of body weight support on normal human gait: development of a gait retraining strategy*, Phys. Ther., 1991, Vol. 71, 824–855.

[7] HAIGHT D.J., LERNER Z.F., BOARD W.J., *A comparison of slow, uphill and fast, level walking on lower extremity biomechanics and tibiofemoral joint loading in obese and nonobese adults*, J. Orthop. Res., 2014, Vol. 32(2), 324–330.

[8] HONG Y., LI J.X., *Influence of load and carrying methods on gait phase and ground reactions in cildren's stair walking*, Gait and Posture, 2005, Vol. 22, 63–68.

[9] KOWALK D.L., DUNCAN J.A. MCCUE F.C., VAUGHAN C.L., *Anterior cruciate ligament reconstruction and joint dynamics during stair climbing*, Med. Sci. Sports Exerc., 1997, Vol. 29, 1406–1413.

[10] MCFADYEN B.J., WINTER D.A., *An integrated biomechanical analysis of normal stair ascent and descent*, J. Biomech., 1988, Vol. 21, 733–744.

[11] MOFFET, H., RICHARDS C.L., MALOUIN F. BRAVO G., *Load carrying during stair ascent: a demanding functional test*, Gait and Posture, 1993, Vol. 1, 35–44.

[12] NADEAU S., MCFADYEN B.J., MALOUIN F., *Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking?*, Clin. Biomech., 2003, Vol. 18, 950–959.

[13] POWERS C.M., BOYD L.A., TORBURN L., PERRY J., *Stair ambulation in persons with transtibial amputation: an analysis of the Seattle Lightfoot*, J. Rehabil. Res. Dev., 1997, Vol. 34, 9–18.

[14] RIENER R., RABUFFETTI M., FRIGO C., *Stair ascent and descent at different inclinations*, Gait and Posture, 2002, Vol. 15, 32–44.

[15] SILDER A., BESIER T., DELP S.L., *Predicting the metabolic cost of incline walking from muscle activity and walking mechanics*, J. Biomech., 2012, Vol. 45, 1842–1849.

[16] SPANJAARD M., REEVES N.D., VAN DIEEN J.H., BALTZOPOULOS V., MAGANARIES C.N., *Lower-limb biomechanics during stair descent: influence of step-height and body mass*, J. Exp. Biol., 2008, Vol. 211, 1368–1375.

[17] SPANJAARD M., REEVES N.D., VAN DIEEN J.H., BALTZOPOULOS V., MAGANARIES C.N., *Influence of gait velocity on gastrocnemius muscle fascicle behaviour during stair negotiation*, J. Electromyogr. Kinesiol., 2009, Vol. 19, 304–313.

[18] SUTHERLAND D.H., *The evolution of clinical gait analysis*, Part 1: *Kinesiological EMG*, Gait and Posture, 2001, Vol. 14, 61–70.

[19] TOWNSEND M.A., LAINHART S.P., SHIAVI R., *Variability and biomechanics of synergy patterns of some lower-limb muscles during ascending and descending stairs and level walking*, Med. Biol. Eng. Comput., 1978, Vol. 16, 681–688.

[20] VAUGHAN C.L., DAVIS B.L., O'CONNOR J.C., *Dynamics of Human Gait*, second ed., Cape Town, South African, 1999.