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Application of gait video-based analysis to improve walking distance in patients with intermittent claudication

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Introduction Intermittent claudication (IC) is a condition of ischemic symptoms in the lower limbs associated with increasing pain in limbs due to physical loading (walking, running and mounting) that relieves after some rest. Dosed walking is recommended as a primary treatment to prevent possible complications in such patients. The **purpose** of this work was to investigate the effect of different targeted footwear features on the biomechanics of human musculo-skeletal system to define optimal footwear designs for reduction of loading on calf muscles and metabolic needs aimed at increasing painless walking distance. **Method** The study recruited 15 healthy male volunteers aged 25.3 ± 2.73 years for the analysis of kinematics, kinetics and EMG-activity during walking in various types of footwear. Eight subjects with IC were also included. Results were recorded using 16 cameras Oqus 3 + (Qualisys), four Force Platforms AMTI (USA), and an EMG system Noraxon (USA). Data were produced and analysed using QTM, Visual3D (C-Motion), and IBM SPSS Statistics. **Results** This study demonstrated that to reduce the load on the calf muscles and not to change the biomechanics of the knee and femur, the most potentially effective footwear were with the length of the beginning of roll over from the heel to the metatarsal area was equal to 55% of the foot length, shoe heel height of 4.5 cm, angle of lifting toes of 20 degrees ($p < 0.05$). Combination of those footwear conditions resulted in increase of pain-free walking distance by 39 %. **Conclusion** The results showed the potential of the applied system of video analysis for designing orthopaedic footwear.

Keywords: motion, video capture, clinical gait analysis, intermittent claudication, orthopaedic footwear

INTRODUCTION

Critical ischemia of the lower limb tissues that may even result in gangrene is observed in 10–14 % of patients with the disease duration from three to 5 years [1]. Occlusive diseases of lower limb arteries take the second place in the structure of disabilities [2, 3].

Intermittent claudication (IC) is one of the syndromes of atherosclerotic lesions of the lower limb arteries, accounting for about 20 % of all cardiovascular diseases. It develops in 0.9-7 % of individuals, depending on age group [4].

There are a number of risk factors in the IC development: age over 45 years, smoking, obesity, IC or vascular diseases in the family history, cardiovascular diseases and/or diabetes mellitus, hypertension, poor diet, hypercholesterolemia [5]. IC is most common in older men, especially in many-years smokers. M. Alzamora stated in his work that the ratio between men and women with IC is approximately 2:1 [6]. According to the literature, IC can be diagnosed in 3 % of people aged 45–64 years and in 18–27 % of those over 60 years old [7]. This fact, as well as a very serious prognosis of atherosclerotic lesions of the lower limb arteries makes early and effective treatment very important. Calf muscles are most symptomatic, causing pain and cramps during walking. The time from the start of walking to the moment when the patient begins to experience pain characterizes the severity of the disease [8]. Pain disappears after a short rest, usually within a few minutes, after which the patient is able to continue walking. Thus, the process of walking consists of successive periods of normal walking, walking accompanied by painful sensations, and periods of forced rest. Pain is unilateral in 40 % and bilateral in 60 % of patients. Patients may also experience a feeling of fatigue or pain in the thigh muscles [9].

All patients with IC will require either conservative or surgical treatment, since 25 % of them may have trophic ulcers, gangrene, and approximately from one to 5 % of patients will need amputation within 5 years [10, 11]. Surgical techniques of revascularization create arterial hyperemia in the extremities by

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increasing the intensity of blood flow, collateral blood supply with improved tissue respiration [12]. Adaptive physical exercises are one of the effective treatment methods, which, according to the literature, was confirmed by a significant increase in the duration of walking untill a forced stop, especially among elderly patients. Daily walks are recommended, ideally for 45 to 60 minutes a day [13]. Dosed walking, that is, walking until the maximum ischemic pain appears (evidence class I) is recommended as an initial treatment for patients with intermittent claudication (level of evidence A) [14, 15]. A positive effect was observed with both endurance exercises [16, 17], and with short-term complex exercises [18]. Therapeutic walking should be combined with medication therapy [19, 20]. Adaptive mechanisms for physical exercise in patients with intermittent claudication include development of collateral circulation, improvement in the function of the vascular endothelium, metabolic and morphological changes in skeletal muscles [21, 22].

Severe pain in the calf muscles may dramatically demotivate a patient to continue therapeutic walking or training [23]. Therefore, footwear that reduces the work of the calf muscles and their need for oxygen, increases duration of ambulation, thereby training the cardiovascular system and the general condition of the patient, would be helpful in such condition.

Investigations of the effect of footwear on changes in kinematics, kinetics, and EMG data are found in the literature. However, the studies do not define which design feature influences what, as the shoes with several changes at the same time were tested. Also, no complete spectrum of such data as kinematics, kinetics and EMG was analyzed. It is worth noting that not every study controlled the walking speed, so effects could be related to the walking speed and not to the footwear tested. According to the available literature, it is not possible to differentiate which shoes can unload the work of the calf muscles but will not reduce the walking speed.

In patients with IC, the proportion of muscle fiber types changes while tissue metabolism, muscle mass and strength decrease [24]. Compared with healthy people, their average walking speed is 27 % slower and 40 % more oxygen is consumed during walking [25].

Our study was aimed at investigating the effect of footwear features on changes in the biomechanics of a person's gait, as well as at the work of the muscles of the lower limbs to determine the optimal geometric characteristics that will increase the distance of painless walking and reduce the intensity of pain in IC patients. The "gold" standard in such clinical studies of musculoskeletal system biomechanics is a video-based analysis in combination with power platforms and a system for measuring the electrical activity of muscles (EMG).

MATERIAL AND METHODS

The study was conducted at the clinical and biomechanical laboratory of the University of Salford (England) belonging to NHS (the National Health System). All patients voluntarily signed informed consents to participate in the study. The ethical rationale for the experimental protocol developed and its safety was approved by the university ethics committee (ETHICS APPLICATION HSCR12/04 *An investigation into the relationship between footwear features and lower limb muscle action and activity*. April 2012 [20].

The study involved 15 healthy males aged 25.3 ± 2.7 years. Their mean weight and height was 71.3 ± 8.5 kg and 1.74 ± 0.06 m, respectively. Eight IC patients in the mean age of 66 ± 9.9 years (mean height of 1.73 ± 0.1 m and weight of 87.7 ± 17.2 kg) took part in testing painless walking distances. Their diagnosis of atherosclerosis of the femoral, anterior or posterior tibial arteries was confirmed by X-ray angiography. They complained of pain in the lower leg after walking the distances of 10 to 400 m. Before the tests, the patients were given a 20-minute rest to stabilize blood pressure in the lower limbs, and then a short period of time to adapt to the footwear tested. They were first offered to start walking at a comfortable speed. According to the visual scale, the subjects reported on the intensity of pain in the footwear tested during their return to the starting point.

Classic male shoes were adapted for research. We tested shoes with different heel height (1.5 cm, 2.5 cm, 3.5 cm, 4.5 cm, 5.5 cm), different toe elevation angles (10, 15 and 20 degrees), various footwear length roll-over in the metatarsal area (55 %, 62.5 % and 70 %

of the total length of the shoe); we used two pairs of shoes with different grades of sole flexion stiffness in the metatarsal zone, two pairs with different levels of the heel roll over, and also barefoot walking. The control shoes had the following characteristics: a toe angle of 15 degrees; heel height 3.5 cm; sole height in the metatarsal zone 2.5 cm; the beginning of roll over in the metatarsal zone 62.5 % from the total length of the footwear; fully stiff sole (**Fig. 1**).

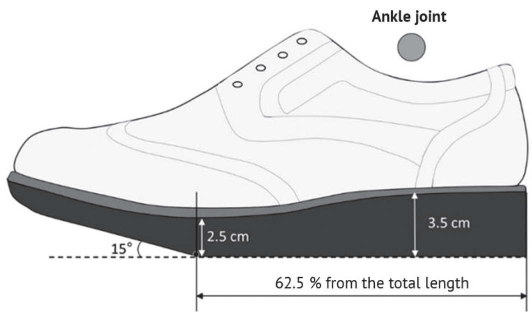

Fig. 1 Control footwear design

Kinematic data were recorded with Oqus 3+ optical cameras (16 Qualisys cameras) with a recording frequency of 100 Hz; kinetic data with AMTI platforms (BP600400, USA) with a frequency of 1000 Hz, muscular activity (tibial, medial head of the gastrocnemius and soleus muscles) with Noraxon's system at 3000 Hz frequency. Walking speed was controlled in the range of ± 2.5 % for all subjects using a laser gate.

The CAST method was used to install passive markers for reconstruction of the human skeleton [26].

Kinematics, kinetics and EMG were analyzed with QTM (Qualisys) and Visual3D (C-Motion) software. A fourth-order Butterworth low-pass filter with a cut-off frequency of 12 Hz was used to remove skin artifacts. To smooth the kinetic data from the platforms, a low-pass filter with a cut-off frequency of 25 Hz was used. EMG analysis was performed using the envelope method (linear envelope) and RMS (Root Mean Square).

The kinematic findings of the ankle, knee and hip joints were normalized to correct the static postures of each subject. Kinetic data were normalized to patient's weight. For EMG signals, the control footwear was a reference, and the maximum value was taken as 100 % on the graphs for comparing the effects of various footwear features. All data on the abscissa were normalized in a percentage range from 0 to 100 %, which corresponded to the full step cycle or phase of the foot support. Each cycle of a step was identified and average values were plotted on the graphs.

IBM SPSS Statistics was used for statistic processing using ANOVA (Repeated measures) with Bonferroni correction, where the significance level was set to $p < 0.05$. A power analysis was conducted, according to which the number of subjects was sufficient, since the results had a normal distribution. Testing was randomized by the subjects and by the sequence of walking recording in various shoes.

RESULTS

A comparative analysis of the effect of footwear features on the work of the ankle and calf muscles is presented in Table 1 and Figure 2.

The results showed that during the foot support phase the ankle is in the position of plantar flexion with an increase in the heel height. An increase in the angle of the toe, as well as a decrease in the length of the beginning of the shoe roll over in the metatarsal zone significantly increased plantar flexion during 40–60 % of the step cycle. Heel height of 4.5 cm reduced the maximum EMG (activity of the medial head of the gastrocnemius muscle) compared to shoes with a heel of 1.5 cm, 2.5 cm and 5.5 cm ($p < 0.05$), as well as the area under the EMG curve in comparison with shoes with a heel of 1.5 cm, 2.5 cm. The maximum activity, as well as the area under the soleus muscle curve in shoes with a heel of 4.5 cm showed a significant decrease by walking as compared to shoes with the heels of 2.5 cm, 3.5 cm and 5.5 cm ($p < 0.05$).

The maximum activity of the medial head of the gastrocnemius and soleus muscles in the shoes with an increased toe angle (20 degrees) showed a significant decrease ($p < 0.05$) when compared with angles of 10° and 15°. The area under the power absorption curve of the ankle joint for footwear with a toe angle of 20° and 55 % of the roll over length in the metatarsal zone also showed a significant decrease as compared to toe angles of 10°, 15° and 62.5 %, 70 % of the shoe length ($p < 0.05$).

The result of the study showed that shoes with a heel height of 4.5 cm, toe angle of 20° and 55 % of the length of the footwear sole before the metatarsal zone bending begins reduced the work of the calf muscles, changed the angular locomotion of the ankle as well as the area of external moments as compared to all other footwear changes to a large extent if Bonferroni's correction was not used.

The results of testing shoes with features that facilitate the work of the calf muscles in IC patients are presented in Figure 3.

All eight participants demonstrated an increase in painless walking by 39.2 % compared with control shoes ($p = 0.01$). Pain was also significantly lower when walking in test shoes ($p < 0.01$) than when walking in control footwear. The average pain values in the control shoes were 7.75 points (standard deviation = 0.87) on a scale from 1 to 10. Experimental shoes reduced this indicator by 3.3 points down to 4.41 (standard deviation = 1.64).

Table 1

Angles and ankle joint moment (AJ) in the sagittal plane, EMG activity of the medial head of the gastrocnemius muscles for various shoe designs: the number outside the brackets is the average value, the standard deviation is in brackets (μ (± SD))

Biomechanical parameters	Footwear				
Indexed values are statistically significant	1	2	3	4	5
Heel height	**1.5 см (1)**	**2.5 см (2)**	**3.5 см (3)**	**4.5 см (4)**	**5.5 см (5)**
Max EMG of the medial head of the gastrocnemius (%)	104.2 (13.7)[4]	110.1 (11.8)[4]	100.0 (8.8)[5]	93.5 (9.1)[1,2,5]	108.1(9.6)[3,4]
Area under the EMG curve of the medial head of the gastrocnemius (%)	114.4 (13.0)[4]	107.4 (9.1)[4]	100.0 (10.1)	92.6 (10.5)[1,2]	103.6 (10.5)
Max EMG of the soleus (%)	104.7 (11.0)	105.8 (9.0)[4]	100.0 (6.5)[4]	91.2 (7.3)[2,3,5]	107.5 (7.4)[4]
Area under the EMG curve of the soleus (%)	109.6 (8.6)	105.5 (7.7)[4]	100.0 (7.3)[4]	94.2 (7.0)[2,3,5]	105.8 (7.7)[4]
Max extension moment in AJ (H*m/kg)	1.41 (0.05)[2,3,4,5]	1.37 (0.04)[1]	1.41 (0.05)[1]	1.40 (0.05)[1]	1.42 (0.04)[1]
Area under curve of AJ flexion moment (%)	128.0 (3.8)[2,3,4,5]	104.7 (5.5)[1,4,5]	100.0 (5.9)[1]	95.1 (5.4)[1,2]	95.4 (5.1)[1]
Area under curve of AJ power generation (%)	118.9 (11.7)[3,4,5]	111.6 (9.8)[3,4,5]	100.0 (9.2)[1,2,4]	90.6 (12.3)[1,2,3]	93.5 (11.1)[1,2]
Area under curve of AJ power absorption (%)	90.7 (14.0)[5]	88.2 (11.5)[3,4,5]	100.0 (13.4)[2]	105.6 (10.9)[2]	108.9 (14.0)[1,2]
Max. AJ motion range full step cycle (°)	26.5 (1.6)[3,4,5]	25.2 (1.4)[4,5]	23.8 (1.5)[1]	23.4 (1.1)[1,2]	23.0 (1.1)1,2
Max. KJ flexion in heel-off phase (°)	58.1 (2.8)[2,3,4,5]	52.3 (2.4)[1,2,4,5]	50.7 (2.6)[1,3,4,5]	46.7 (3.0)[1,2,3,5]	43.6 (3.2)[1,2,3,4]
Toe angle	**10° (1)**	**15° (2)**	**20° (3)**		
Max. EMG of med. head of gastrocnemius (%)	107.2 (9.2)[3]	100.0 (8.8)[3]	89.4 (9.9)[1,2]		
Area under curve of med. head of gastrocnemius (%)	108.0 (11.2)[3]	100.0 (10.1)	93.6 (10.1)[1]		
Max. EMG of soleus (%)	101.4 (7.6)[3]	100.0 (6.5)[3]	92.2(8.0)[1,2]		
Area under EMG curve of soleus (%)	102.2 (7.7)	100.0 (7.3)	96.3 (9.1)		
Max. Extension moment in AJ C (N*m/kg)	1.45 (0.05)[2,3]	1.41 (0.05)[1,3]	1.26 (0.04)[1,2]		
Area under curve of AJ flexion moment (%)	105.4 (5.4)[2,3]	100.0 (5.9)[1,3]	92.5 (4.1)[1,2]		
Area under curve of AJ power generation (%)	107.7 (9.1)	100.0 (9.2)	102.0 (10.6)		
Area under curve of AJ power absorption (%)	111.1 (11.8)[2,3]	100.0 (13.4)[1,3]	79.8 (11.0)[1,2]		
Max. AJ motion range in full step cycle (°)	25.3 (1.2)	23.8 (1.5)	24.7 (1.6)		
Max. KJ flexion in heel-off phase (°)	50.8 (2.8)	50.7 (2.6)	50.7 (3.7)		
Distance up to bending in the metatarsal zone	**55 % (1)**	**62.5 % (2)**	**70 % (3)**		
Max. EMG of med. head of gastrocnemius (%)	91.3 (11.3)[2,3]	100.0 (8.8)[1]	107.1 (9.3)[1]		
Area under curve of med. head of gastrocnemius (%)	91.1 (12.6)[3]	100.0 (10.1)	106.7 (9.0)[1]		
Max. EMG of soleus (%)	94.7 (9.4)	100.0 (6.5)	98.2 (8.3)		
Area under EMG curve of soleus (%)	97.6 (6.8)	100.0 (7.3)	99.4 (8.3)		
Max. Extension moment in AJ C (N*m/kg)	1.35 (0.05)[2,3]	1.41 (0.05)[1,3]	1.44 (0.03)[1,2]		
Area under curve of AJ flexion moment (%)	94.3 (5.4)[2,3]	100.0 (5.9)[1,3]	106.4 (5.1)[1,2]		
Area under curve of AJ power generation (%)	104.9 (9.5)[3]	100.0 (9.2)	94.6 (10.2)[1]		
Area under curve of AJ power absorption (%)	91.4 (11.4)[2,3]	100.0 (13.4)[1,3]	113.8 (11.5)[1,2]		
Max. AJ motion range in full step cycle (°)	24.1 (1.1)	23.8 (1.5)	24.5 (1.3)		
Max. KJ flexion in heel-off phase (°)	49.3 (3.1)	50.7 (2.6)	51.8 (2.5)		
[1,2,3,4,5] – Show statistical significance between tested shoe features with Bonferroni correction, $p < 0.05$					

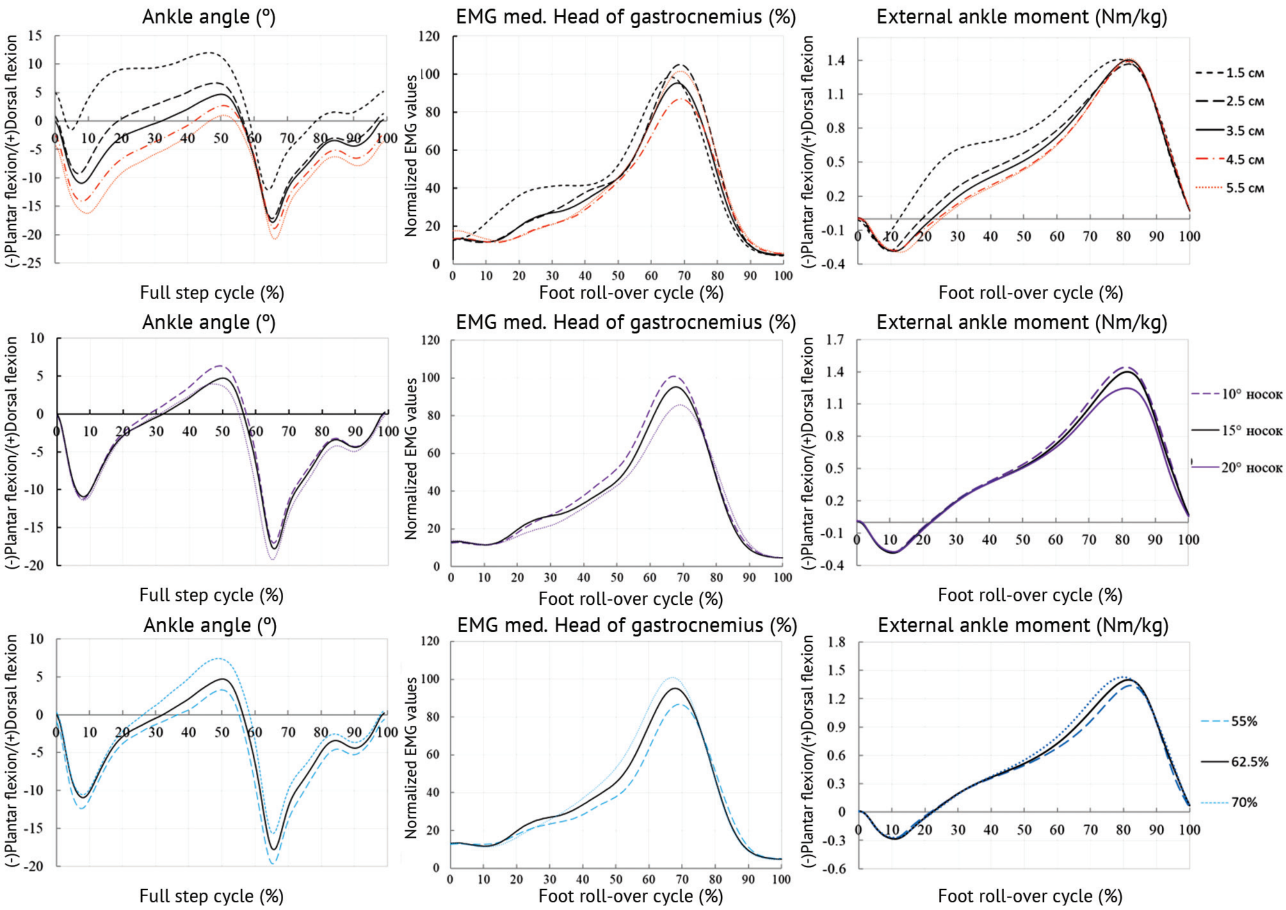

Fig. 2 Graphs of a comparative analysis of angular changes in the ankle in the sagittal plane; EMG activity of the medial head of the gastrocnemius and external relative moment of force in the sagittal plane for shoes with different heel heights (1.5 cm, 2.5 cm, 3.5 cm, 4 , 5 cm, 5.5 cm), different toe angles (10, 15 and 20 degrees), different distances before the start of roll over in the metatarsal area (55 %, 62.5 % and 70 % of the total length of the shoe)

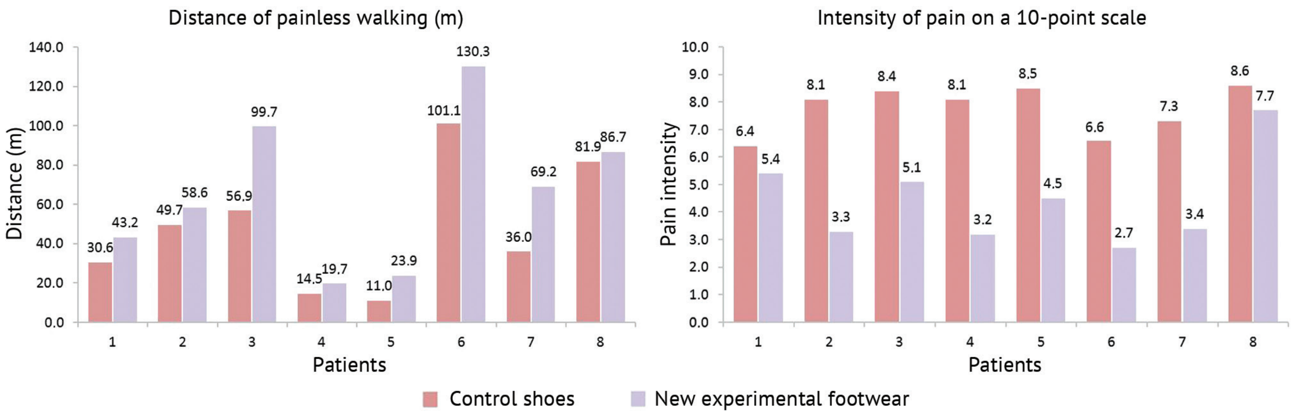

Fig. 3 Distance of painless walking and the intensity of pain for the control shoes and new experimental footwear

DISCUSSION

The study demonstrated how geometric changes in shoe design influence kinematics, kinetics, and EMG-activity of the ankle joint. The aim of the work was to determine the optimal parameters of the footwear to reduce the work of the calf muscles.

The results show that the toe angle of 20°, the height of the heel of 4.5 cm and a 55 % length of the sole before the metatarsal zone begins to roll over significantly decrease the work of the medial head of the gastrocnemius and soleus muscles in all subjects. It is worth emphasizing that a 4.5 cm high heel reduced the work of the calf muscles. But adding only 1 cm to its height greatly increased the load on the same muscles, despite the fact that the height of the heel reduces the distance of the lever of the support force point to the center of the ankle joint, which, in turn, should have reduced muscle work. The maximum values of muscle strength are determined by the length of the muscle fibers, as well as by the angle between the line coinciding with the direction of the tendon pull and the vector of the force developed by the fiber prior to contraction. When an active striated muscle is stretched, its force first increases and then falls, and the maximum of the values ("Blix maximum") is reached with the natural (normal) length of the muscle (rest length). Normal "Blix maximum" is registered when the foot is at an angle of 95° of plantar flexion [27]. With skeletal muscle contraction by 15 % of the neutral length (without stretching and contraction), the maximum generation force loses approximately 50 % [28]. When walking on a high heel, the calf muscles have more power parameters, despite the fact that the necessary time to perform plantar flexion of the joint is much less than when compared with walking in shoes with lower heels.

Shoes with 55 % before the start of the roll-over in the metatarsal zone showed a decrease in the work of the gastrocnemius muscles. This effect can be achieved due to the fact that the phase of the plantar flexion at 30–60 % of the full step cycle begins earlier owing to the geometrical change of the footwear. Therefore, in the first place, the lever of the ankle moment and, consequently, of the moment itself (muscle force multiplied by the lever of the moment) decreases. It is also easier for the foot to execute plantar flexion without the use of muscles due to the anatomical structure of the shoe, which reduces the load on the calf muscles. Almost the same effect is obtained with an increase in the angle of the toes; the reduction of the work of the gastrocnemius muscles is achieved due to a simpler entrance of the joint into the plantar flexion during the final phase of the foot roll-over cycle, that is, an anatomically simplified push of the more natural foot roll and reduction of the moment of movement in the ankle joint is performed.

Clinical tests of experimental footwear with the most effective geometrical parameters of the design of the sole, which reduce the work of the calf muscles, showed a positive result.

CONCLUSION

The work showed the potential of using a video-based analysis system for developing orthopedic shoes. The results of the study demonstrated that the work of the calf muscles decreases in young men wearing the shoes with a heel height of 4.5 cm (height in the metatarsal zone 2.5 cm), a toe angle of 20 degrees and the beginning of the curve (roll-over) in the metatarsal region equal to 55 % of the total length of the footwear. Clinical trials of experimental shoes with these characteristics showed a positive result, increasing the distance of painless walking by 39 % in IC patients and reducing the intensity of pain in the calf muscles by one half.

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