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The Effect of Custom Orthotic Insoles on Lower Limb Muscle Fatigue in Patients with Flat Feet

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Abstract

Flat feet, a common foot structural abnormality, seriously affects an individual's health and quality of life. This study aims to evaluate the impact of custom orthotic insoles on sports biomechanical characteristics such as muscle fatigue in patients with flat feet. A self-controlled crossover design was adopted, with a 25-year-old male patient with flexible flat feet as the subject. In two experiments separated by one week, the subject wore ordinary insoles (control group) and custom orthotic insoles (experimental group) respectively, and ran continuously on a treadmill at 8 km/h for 30 minutes. Surface electromyographic (sEMG) signals of the gastrocnemius muscle (sampling rate: 2000 Hz) and plantar pressure data were collected simultaneously. Indicators including integrated electromyography (iEMG), maximum iEMG, mean frequency (MF), and plantar peak pressure were compared. In the early stage of exercise (1–6 minutes), the iEMG of the experimental group was significantly higher than that of the control group [(16,096.78 ± 1,235.73) vs (9,908.63 ± 531.04)], with an increase of 62.45% ($p < 0.001$); the maximum iEMG increased by approximately 101% [(675.68 ± 129.35) vs (335.77 ± 34.58), $p < 0.001$]. In the late stage of exercise (7–30 minutes), the iEMG of the control group surged to (27,434.87 ± 11,424.37), while that of the experimental group remained at (16,409.57 ± 1,436.47), with a near-significant difference ($p = 0.052$). The decrease amplitude of MF in the control group was approximately 40% higher than that in the experimental group, and the increase in fatigue slope was more than 112 times. The average plantar peak pressure in the experimental group decreased by about 12%, and the center of gravity trajectory was closer to the midline. These results indicate that custom orthotic insoles can effectively optimize plantar pressure distribution, delay the occurrence of muscle fatigue, and may improve neuromuscular control efficiency. This study confirms the positive role of custom orthotic insoles in improving exercise performance and reducing the risk of sports injuries in patients with flat feet.

Keywords

Flat feet; Custom insoles; Plantar pressure; Surface electromyography (sEMG); Muscle fatigue

1. Introduction

Flat feet, also known as fallen arches, is a common foot structural abnormality characterized by a reduction or disappearance of the arch height. Statistics show that the incidence of flat feet among adolescents is as high as 10%-20%, which has become a significant issue affecting health and quality of life [1]. The collapse of the foot arch not only causes foot pain and abnormal gait but may also trigger a chain reaction in the knee joint, hip joint, and even the spine, leading to long-term motor and functional impairments [2]. In recent years, with changes in lifestyle and increasing sports demands, flat feet have gradually become a focus of attention in the fields of sports medicine, rehabilitation medicine, and biomechanics.

Studies have shown that wearing appropriate orthotic insoles can correct the feet of flat feet patients to a certain extent, improving plantar pressure distribution and gait characteristics [3]. However, there is currently no unified view on the mechanism by which orthotic insoles affect the biomechanical properties of flat-footed individuals, and in particular, their intervention effects on lower limb joint and muscle function still require further research [4]. In addition, there is a significant correlation between plantar pressure and plantar sensation in flat feet patients: increased pressure load on the foot arch leads to a decrease in the plantar sensory threshold, which may further increase the risk of foot fatigue and injury [5]. In recent years, foreign studies have also indicated that abnormalities in foot structure and function have a significant impact on plantar pressure distribution, thereby increasing long-term health risks [6]. Furthermore, as a non-surgical intervention, orthotic insoles are increasingly used in the treatment of foot pain, but their efficacy and cost-effectiveness still need further verification [7].

Although research on flat feet has made some progress, existing treatment and correction methods still have many shortcomings. For example, the design and clinical application of traditional orthotic insoles lack personalized considerations and cannot provide effective support for different types of flat feet [3]; at the same time, there are relatively few studies on the impact of orthotic insoles on lower limb motor function, and in particular, their compensatory effect on the knee and hip joints has not received sufficient attention [4]. In addition, the foot muscle fatigue of flat feet patients intensifies significantly during long-term walking or exercise—this phenomenon has not been thoroughly studied, and effective relief strategies are even more lacking [5]. These issues highlight the need to further explore the mechanism of flat feet and its correction methods.

This study focused on flat feet patients and evaluated the biomechanical effects of special insoles by comparing plantar pressure distribution and muscle activity characteristics when wearing custom orthotic insoles (experimental group) and ordinary insoles (control group). The study used a plantar pressure measurement system (PP system) and surface electromyography (EMG) technology to simultaneously collect plantar pressure data and gastrocnemius EMG signals during a standardized running test, with a focus on analyzing the dynamic changes in integrated electromyography (iEMG), maximum activation peak (max iEMG), and mean frequency (Mean Frequency).

2. Experimental Methods

This experiment aims to evaluate the effect of orthotic insoles on relieving plantar pressure, improving gait, and reducing muscle fatigue by measuring the plantar pressure distribution and muscle fatigue of a flat-footed patient when wearing custom orthotic insoles and ordinary insoles. The subject of the experiment was a flat-footed patient (the author him/herself). The experiment was conducted twice with a one-week interval to ensure the subject's physical condition recovered.

2.1 Experimental Equipment and Materials

For plantar pressure measurement, the Novel Pedar system was used, which measures plantar pressure distribution in real time through orthotic pressure insoles. A NORAXON surface electromyography (sEMG) system (with a sampling rate of 2000 Hz) was simultaneously employed to monitor the gastrocnemius muscle. A treadmill with adjustable speed was used to simulate the running environment. Two types of insoles were utilized: ordinary flat insoles (for the control group) and custom orthotic insoles (for the experimental group). The custom orthotic insoles were tailored to the subject's foot shape, featuring a curved bottom design, and were suitable for flat shoes. Flat shoes were used to hold the insoles, ensuring consistent shoe type between the control group and the experimental group.

2.2 Experimental Procedures

2.2.1 Plantar Pressure Measurement

The control group was tested while wearing ordinary flat insoles, and the experimental group was tested while wearing custom orthotic insoles. The pressure insoles of the PP (Plantar Pressure) system were placed inside the flat shoes to ensure full contact between the insoles and the plantar surface. After putting on the insoles, the subject ran on the treadmill at a fixed speed (8 km/h) for 30 minutes. The system recorded plantar pressure distribution data in real time, including pressure peaks, center of pressure (COP) trajectory, and other parameters. Baseline EMG data were collected (with the subject standing statically for 30 seconds) before and after each test, and a crossover design (AB/BA sequence) was adopted to eliminate order effects.

2.2.2 Muscle Fatigue Measurement

Muscle fatigue measurement is typically based on the analysis of changes in EMG signal characteristics, and a surface electromyography (sEMG) system was used to monitor the activity of target muscles in real time. For the experiment, a wireless dual-channel sEMG device (Noraxon MyoMotion) was selected. The sampling rate was set to 2000 Hz to meet the requirements of frequency-domain analysis, the bandwidth was controlled within the range of 10–500 Hz, and the common-mode rejection ratio (CMRR) was required to be > 110 dB.

Electrode placement strictly followed anatomical standards: electrodes for the lateral head of the gastrocnemius muscle were placed 2 finger-widths below the popliteal fossa, aligned with the direction of muscle fibers. Before electrode attachment, the skin was thoroughly cleaned with alcohol swabs to reduce impedance.

A multi-parameter fusion strategy was adopted for fatigue evaluation: The normalized Root Mean Square (RMS) value (the percentage of the current value relative to the maximum value) was mainly analyzed; an increase of more than 15% indicated significant fatigue. Changes in the Median Frequency (MF) were tracked, and the frequency shift ratio during running was calculated (the percentage of the difference between the initial MF and the current MF relative to the initial value); a decrease of more than 10% was statistically significant. Meanwhile, a nonlinear dynamic parameter, the entropy change index, was introduced to reflect changes in neuromuscular coordination.

To eliminate individual differences, all indicators were standardized with reference to the baseline test values. During the treadmill running process, feature values were automatically calculated in segments every 30 seconds, and a fatigue development curve was established using a sliding window algorithm. The synchronously collected plantar pressure data and EMG signals were time-aligned to achieve gait cycle matching, with a focus on analyzing changes in the activation pattern of muscles related to the ankle push-off phase.

2.2.3 Test Parameters

All tests were conducted on a treadmill at a constant speed of 8 km/h. To ensure the subject's physical condition fully recovered and eliminate potential cumulative fatigue effects, a one-week interval was set between the two tests. The plantar pressure and surface electromyography (sEMG) signals collected synchronously during each test were uniformly exported and properly stored after the experiment for subsequent offline analysis.

3. Results and Discussion

Figure 1 and Table 1 compare the variation trends of the integrated electromyography (iEMG) values of muscle activity under two conditions: without insoles and with insoles. A total of 10 time periods (3 minutes per period) were recorded.

In the early stage of the experiment (Phase 1, T1-T6), the average iEMG of the insole group (16,096.78) was significantly higher than that of the no-insole group (9,908.63), an increase of approximately 62.45%. This indicates that in the initial stage of the experiment, wearing insoles may have altered the biomechanical environment of the plantar region, requiring muscles to adapt and stabilize gait with a higher activation level—this is consistent with the hypothesis of initial adaptive adjustment of muscles.

In the late stage of the experiment (Phase 2, T7-T10), the average iEMG of the no-insole group soared to 27,434.87, while that of the insole group remained at a stable level (16,409.57). The standard deviation of the no-insole group also increased sharply (11,424.37), reflecting that during this phase, muscle activity was not only of high intensity but also extremely unstable—a typical characteristic of muscles entering a fatigued state.

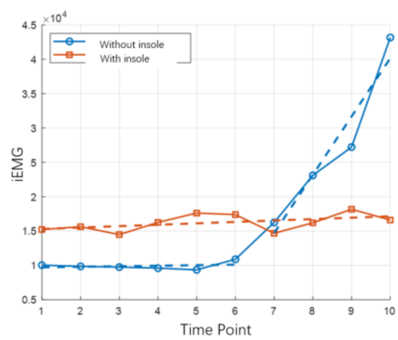

Figure 1. Variation Trend of iEMG with and without Insoles.

Table 1. Experimental Data Analysis Table of the Effect of Insoles on iEMG Values

Analysis Dimension	Comparison Group/Phase	Mean Value	Standard Deviation	Key Quantitative Indicator (Difference/Rat)	p-value	Conclusion
Descriptive Statistics	Phase 1 – No-insole Group	9908.63	531.04	-	-	-
	Phase 1 – Insole Group	16096.78	1235.73	Insole group was 62.45% higher than no-insole group on average	-	-
	Phase 2 – No-insole Group	27434.87	11424.37	No-insole group was 67.19% higher than insole group on average	-	-
	Phase 2 – Insole Group	16409.57	1436.47	-	-	-
Hypothesis Testing	Phase 1: Insole Group vs. No-insole Group	-	-	-	0.0000	Significant difference
	Phase 2: No-insole Group vs. Insole Group	-	-	-	0.0520	No significant difference
	No-insole Group (Intra-group): Phase 2 vs. Phase 1	-	-	-	0.0024	Significant difference
Trend Analysis (Fatigue Accumulation Rate)	No-insole Group – Phase 1	-	-	Rate = 75.62; Rate in Phase 2 was 112.25 times of this	-	-
	No-insole Group – Phase 2	-	-	Rate = 8,487.85 (explosive growth)	-	-
	Insole Group – Entire Period	-	-	Rate = 205.44 (stable trend)	-	-

Mean iEMG reflects the overall intensity of muscle activity, i.e., the continuous activation level. As shown in Figure 2 and Table 2, similar to the iEMG results, in the early stage of the experiment (Phase 1, T1-T6), the Mean EMG of the insole group (89.43) was significantly higher than that of the no-insole group (55.05). This indicates that in the initial stage, muscles adapted to the new environment brought by the insoles, and their continuous electrical activity level also increased accordingly. In the late stage of the experiment (Phase 2, T7-T10), the average Mean EMG of the no-insole group rose to 152.42, and the standard deviation also increased significantly (61.88), indicating that the continuous activation level of muscles not only doubled but also the activity state was highly unstable. In contrast, the Mean EMG of the insole group only slightly increased from 89.43 to 91.17.

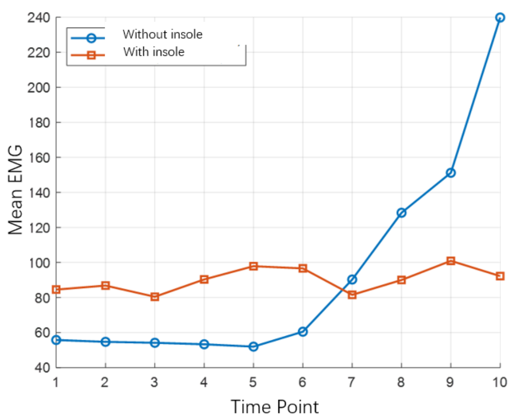

Figure 2. Variation Trend of Mean EMG with and without Insoles.

Table 2. Experimental Data Analysis Table of the Effect of Insoles on Mean EMG Values

Analysis Dimension	Comparison Group/Phase	Mean Value	Standard Deviation	Key Quantitative Indicator (Difference/Rat)	p-value	Conclusion
Descriptive Statistics	Phase 1 – No-insole Group	55.05	2.95	-	-	-
	Phase 1 – Insole Group	89.43	6.86	The insole group was approximately 62.45% higher on average than the no-insole group	-	-
	Phase 2 – No-insole Group	152.41	63.47	The no-insole group was approximately 67.17% higher on average than the insole group	-	-
	Phase 2 – Insole Group	91.17	7.98	-	-	-
Hypothesis Testing	Phase 1: Insole Group vs. No-insole Group	-	-	-	0.0000	Significant difference
	Phase 2: No-insole Group vs. Insole Group	-	-	-	0.0520	No significant difference
	No-insole Group (Intra-group): Phase 2 vs. Phase 1	-	-	-	0.0024	Significant difference
Trend Analysis (Fatigue Accumulation Rate)	No-insole Group – Phase 1	-	-	Growth slope = 0.42; the slope in Phase 2 was approximately 112.26 times this value	-	-
	No-insole Group – Phase 2	-	-	Growth slope = 47.15	-	-
	Insole Group – Entire Period	-	-	Growth slope = 1.14	-	-

Figure 3 and Table 3 demonstrate that the max iEMG of the insole-wearing group and the insole-free group exhibited significantly different dynamic patterns. In the early stage of the experiment (Phase 1, T1–T6), the average max EMG of the insole-wearing group (675.68) was much higher than that of the insole-free group (335.77). This result is consistent with the observations of iEMG and Mean EMG. In the late stage of the experiment (Phase 2, T1–T6), the average max EMG of the insole-free group more than doubled, reaching 801.87, accompanied by large fluctuations (standard deviation = 320.19). In contrast, the max RMS (Root Mean Square) value of the insole-wearing group even decreased slightly (637.76). By comparison, the max iEMG of the insole-wearing group remained stable within the range of 524.79–844.02 μVs after Time Point 7.

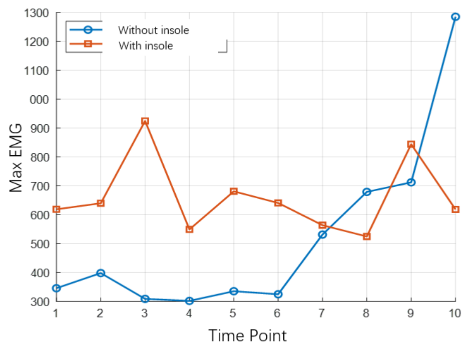

Figure 3. Variation Trend of Max EMG with and without Insoles.

Table 3. Experimental Data Analysis Table of the Effect of Insoles on Max EMG Values

Analysis Dimension	Comparison Group/Phase	Mean Value	Standard Deviation	Key Quantitative Indicator (Difference/Rat)	p-value	Conclusion
Descriptive Statistics	Phase 1 – No-insole Group	335.77	34.58	-	-	-
	Phase 1 – Insole Group	675.68	129.35	The average value of the insole-wearing group was approximately 101.23% higher than that of the insole-free group.	-	-
	Phase 2 – No-insole Group	801.87	331.56	The average value of the insole-free group was approximately 25.73% higher than that of the insole-wearing group.	-	-
	Phase 2 – Insole Group	637.76	142.77	-	-	-
Hypothesis Testing	Phase 1: Insole Group vs. No-insole Group	-	-	-	0.0000	Significant difference
	Phase 2: No-insole Group vs. Insole Group	-	-	-	0.1992	No significant difference
	No-insole Group (Intra-group): Phase 2 vs. Phase 1	-	-	-	0.0039	Significant difference
Trend Analysis (Fatigue Accumulation Rate)	No-insole Group Phase 1	-	-	Growth slope = -8.55 (slight decrease); the slope of Phase 2 was approximately 26.83 times the absolute value of this slope.	-	-
	No-insole Group – Phase 2	-	-	Growth slope = 229.42	-	-
	Insole Group – Entire Period	-	-	Growth slope = -3.45	-	-

Figure 4 illustrates the variation of the mean frequency of muscle EMG signals with exercise time when subjects wore insoles and when they did not. As can be seen from the data,For both the insole-free group and the insole-wearing group, the mean frequency of muscles decreased with the increase of exercise time. The initial frequency of the insole-free group (272.24 Hz) was slightly lower than that of the insole-wearing group (272.76 Hz), but its subsequent decline rate was faster—indicating a more pronounced muscle fatigue process in the insole-free group. Throughout the entire test period (10 measurement points), the mean frequency of the insole-wearing group remained more stable and showed a smaller final decline amplitude, whereas the insole-free group exhibited a more significant decline. Notably, in the late stage of the test (Points 7–10), the frequency decline rate of the insole-free group was even faster, which indicates a more severe fatigue accumulation effect.

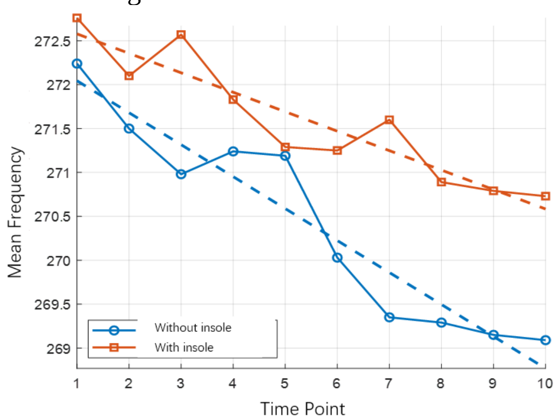

Figure 4. Variation Trend of Mean Frequency with and without Insoles.

4. Conclusions

By integrating kinematic parameter tracking, electromyographic (EMG) signals, and EMG mean frequency, the following conclusions can be drawn: the intervention of insoles exerts a significant impact on sports performance and muscle fatigue, which is mainly reflected in two aspects: optimizing the biomechanical pattern and delaying the fatigue process.

Firstly, insoles contribute to maintaining more stable kinematic characteristics. The motion parameters of the insole-free group showed a more obvious downward trend over time. by realigning the body's center of gravity during dynamic movement, it minimizes the need for the body to adopt abnormal compensatory motions to maintain stability. In addition, insoles may buffer the ground reaction force, reduce the unnecessary load on joints and soft tissues during exercise, and further delay the decline in sports performance.

Secondly, insoles significantly slow down muscle fatigue. The analysis of EMG signals revealed that the muscle activation level of the insole-free group decayed more rapidly, while the fatigue trend of the insole-wearing group was much gentler. Meanwhile, the change in EMG mean frequency further confirms that the use of insoles can slow down the loss of high-frequency motor units and make the muscle contraction pattern more efficient.

Furthermore, insoles may improve exercise economy by optimizing neuromuscular control. The smaller magnitude of frequency decline in the insole-wearing group implies that insoles may help maintain the coordination of the neuromuscular system and reduce unnecessary energy consumption.

In summary, insoles can optimize mechanical support, delay muscle fatigue, and improve exercise economy during exercise, which play a positive role in enhancing sports performance and reducing the risk of sports injuries. Future studies can further integrate dynamic analysis and fatigue perception scales to more comprehensively evaluate the impact of insoles on exercise physiology and psychology.

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