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Research Article

The Influence of Short-term Restriction of Unilateral First Metatarsophalangeal Joint on the Contralateral Lower Limb Joints

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Abstract

To study the effect of restriction of unilateral movement of the first metatarsophalangeal joint (FMJ) on the biomechanics and gait of the contralateral lower limb. 8 adult college students completed walking with barefoot and left foot FMJ constraint (FMJC) respectively. The time node for collecting gait and biomechanical parameters is (I) 0min barefoot walking, (II) Walk immediately with FMJC at 0min, (III) walk after 30min with FMJC, (IV) walk barefoot after 30min with FMJC; Calculate the gait parameters on the contralateral side of the FMJC, the net joint torque and the joint moment arms of the hip, knee and ankle joints. Compared with the time node I, the maximum dorsiflexion angle and the maximum plantar flexion angle of the unrestricted side ankle joint at time node III increased significantly ($p<0.05$), and the maximum plantar flexion moment and maximum dorsiflexion moment increased significantly ($p<0.05$), the power of the ankle joint increased significantly ($p<0.05$); the torque and power of the hip and knee joints on the unrestricted side increased significantly ($p<0.05$); On the unrestricted side, there was no significant difference in stride length, swing phase, support phase and step length ($p>0.05$).

Short-term unilateral FMJC will cause biomechanical compensation and compensation transmission in the unrestricted lower limb joints. That is, the unrestricted hip, knee, and ankle joints maintain normal gait by strengthening their work, and the transmission of compensation is enhanced from top to bottom.

Keywords: Gait; Metatarsophalangeal joint; Biomechanics; Compensation

Abbreviations: First Metatarsophalangeal Joint Constraint (FMJC); First Metatarsophalangeal Joint (FMJ)

Introduction

When studying the movement of lower body, researchers usually only focus on the movement features of the hip, knee and ankle joints, or simply consider the foot as a whole. At most, the movement of the foot involves only the subtalar(ankle) joint and the subtalar joint, while ignoring the Metatarsophalangeal Joint (MJ) as the joint link between the ground and the lower limbs of the body [1,2]. As we all know, to start running, jumping and other rapid foot flexion movements, the final movement must be in the MJ: The extension of the MT is completed by the contraction of the ankle joint plantar flexor muscles and the toe flexor muscles under the condition of distal fixation, of which the FMJ is the most important joint [3,4].

The role of the FMJ on foot movement cannot be ignored, and its flexion and extension characteristics can have an important impact on the running and jumping movements of the human body, especially the kick-off effect in the later stage of support [5,6]. Recent studies have shown that the FMJ, as the end joint of the human body, basically maintains an extended state during the process of pushing off the ground, so that the joint mainly absorbs energy before it leaves the ground, and the energy generated is almost negligible [7,8]. Study how the FMJ effectively transforms the absorbed energy, and the impact on the mechanical properties of the lower limbs is very meaningful [9,10]. The limited disease of the FMJ is common in various diseases, such as gout, diabetes, etc. [11,12]. The flexion and extension of the MJ will have an important impact on the human body's movement function, mechanical characteristics and other joint compensation of the lower limbs. The destruction of its stability will cause changes in the biomechanical characteristics of the forefoot, including the reduction of the range of motion of the MJ, the change of local plantar pressure, increased pressure around the joints, and then seriously affect the motor function of the foot and cause the functional compensation of the lower limbs [13-15]. Menz *et al*. measured the MJ plantar pressure and joint range of motion of 172 volunteers, analyzed and compared the relationship between the two and concluded that the correlation coefficient between MJ scope of activity and plantar pressure is 0.85 [16]. Budhabhatti *et al*. found through a three-dimensional finite element modeling study that completely restricting the flexion and extension of the FMJ will increase the pressure on the MJ by 223% [17]. Obviously, the importance of MJ to the normal activities of the human body is beyond doubt.

The results of our previous research show that [18], the FMJ constraint (FMJC) condition will increase the energy consumption of the ipsilateral ankle, knee, and hip joints. When the FMJ is restricted, the body mainly performs load generation through the ipsilateral hip, knee, and ankle joints. Compensation and transfer are used to maintain the dynamic balance of kinematics, and the compensation transmission is manifested as the sequential attenuation of the ankle, knee and hip joints. However, we did not study the energy changes of the unrestricted side joints. We assume that the compensation of joint load in the case of left FMJC can be transmitted from the left lower limb to the right lower limb, that is, the right lower limb joints increase work to contribute to the maintenance of the normal gait of the lower limbs. The purpose of this clinical research is to understand the biomechanical connection between the FMJ and the bilateral hip, knee and ankle joints of the lower limbs.

Material and Methods

Inclusion and Exclusion Criteria

We refer to our previous experimental methods [18], Recruit 8 healthy young volunteers to participate in the trial (4 men and women). All subjects were informed of the trial process and requirements in advance. The trial was conducted after the subjects' consent was obtained. The ethics committee of the Second Hospital of Jilin University approved the experiment. The subjects had an average age of 23.2±1.1 years, an average height of 172.6±3.1cm, and an average weight of 66.7±6.5kg. They had no history of upper and lower limb nerve and musculoskeletal diseases.

Study Design

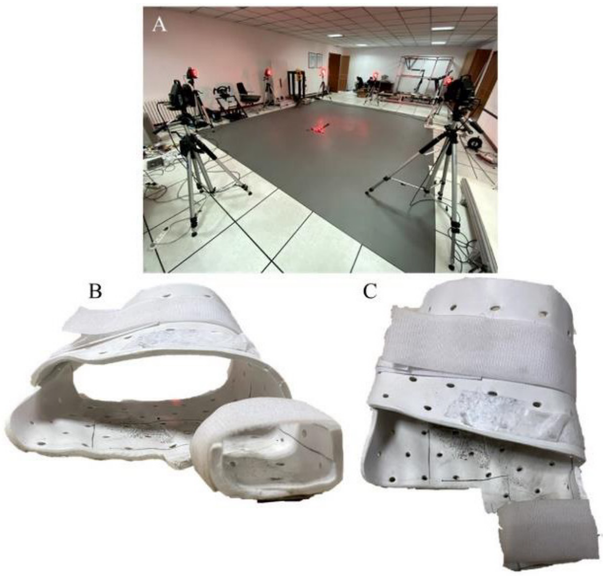

Figure 1: Gait analysis laboratory (A), FMJC brace (B, C).

The equipment used in this experiment is mainly composed of the gait walking test bench (Figure 1A), the data acquisition system, and the FMJC device (Figure 1BC). The FMJC device used in the test consists of a low-temperature thermoplastic sheet provided by Convalesce®, medical gauze and Velcro marking points. During the research, the FMJC was made according to the foot shape of each subject, thereby restricting the movement of the FMJ. The data acquisition system consists of a Vicon 3D optical motion capture system, which includes 6 MX infrared cameras and two AMTI biomechanics force plates. The force plate used to collect gait parameters has a collection frequency of 1000 Hz and a size of 464 mm×508 mm. The total length of the gait walking test bench is 5m, the width is 2m, and the height is 2.5m. The force plate is embedded in the walking test bench, and the angle of the force plate ground can be adjusted to ensure that the force plate and the surface of the test bench are in a horizontal plane.

Experimental Process

Before the gait analysis started, the experimenter calibrated the Vicon system. During the test, the subjects wore swimming trunks and attached 23 reflective marking points on their bodies: Bilateral anterior superior iliac spine, midpoint of the spinous process of the fourth and fifth lumbar vertebrae, bilateral anterior thigh, bilateral lateral femoral condyle, bilateral medial femoral condyle, bilateral tibial tuberosity, bilateral lateral fibular malleolus, bilateral tibia medial malleolus, bilateral toes, bilateral heel, at the same height as the toe, the inner side of the bilateral FMJ, the outside of the bilateral fifth MJ. After attaching the reflective ball, let the subject stand still in the test area with both arms slightly open for about 2s, to build a static model of the subject. Before starting to walk, give the subject appropriate practice time to adapt to the test environment and the position of the force plate, so that the foot can be stepped on the center of the force plate as much as possible to make data collection the most accurate.

The researcher asked the subject to complete the test in a natural and relaxed state, and the data collected in each group should include 3 to 4 gait cycles. Each subject is required to complete 10 walking tests under Bare Foot (BF) and FMJC conditions respectively. The time nodes for collecting gait and biomechanical parameters are (I) 0min barefoot walking, (II) 0min immediate FMJC Walking, (III) Walk after 30min FMJC, (IV) Walk barefoot after 30min FMJC.

At the same time, kinematics and dynamics data are collected through a three-dimensional force plate (Kistler 9281CA, Switzerland, 1000 Hz) and an 8-lens infrared high-speed motion capture system (Motion Analysis Raptor-4 USA, 200 Hz). At the beginning, the subject was about 10 meters away from the force plate in a straight line. After hearing the command, the subject naturally walked through the test area, and the speed through the force plate was controlled at 1.5±0.2m/s. At the specified speed, the subject with normal gait, without any step adjustment, and with the right foot on the table, it is regarded as a valid test. Complete the test under two conditions of normal and MJs in a random order and collect 3 valid data under each condition, the results were averaged 3 times.

Data Analysis

Calculate the three-dimensional angle, joint torque, and joint power of the hip, knee, and ankle joints on the unrestricted side of FMJC. The parameters in the two cases were compared by paired-sample t-test. The significance level was set as the probability of type I error not greater than 0.05, and all statistical analysis was completed with SPSS 24.0 software.

Results and Discussion

Gait parameters of the right lower extremity in the case of FMJC of the left lower extremity Compared with time node (I) 0min barefoot walking, there is no significant difference in the basic gait parameters of the right lower limb when walking with the FMJ on the left side ($p>0.05$) (Table 1).

Table 1: Gait parameters of FMJC on the unrestricted side lower limbs.

Time point	I	II	III	IV
Step length (cm)	82.50±4.50	80.90±2.40	80.60±1.3	82.90±3.4
Step width (cm)	12.50±4.30	13.50±2.10	13.65±2.00	13.50±2.10
Frequency (steps/s)	1.85±0.15	1.90±0.41	1.85±0.50	1.95±0.35
Swing phase (%)	0.45±0.05	0.35±0.065	0.40±0.020	0.40±0.07
Supporting phase (%)	0.75±0.01	0.61±0.02	0.55±0.05	0.60±0.03

Time point：I(0min Bare Foot), II(0minFMJC), III(30minFMJC), IV(Bare Foot after 30min FMJC); Compared with the time point I *$p<0.05$.

Kinematics and Biomechanical Parameters of the Ankle Joint of the Right Lower Extremity in the Case of FMJC of the Left Lower Extremity

The sagittal angle, torque, and power curves of the right lower extremity ankle, knee, and hip joints at the four time points are shown in (Figure 2). Compared with the time node (I) of barefoot walking at 0 minutes, the kinematic and biomechanical parameters of the unrestricted side joints of the lower limbs when the FMJ is restricted to walk show: The maximum ankle dorsiflexion angle is significantly increased ($p<0.05$), and the maximum plantar flexion angle decreased significantly; The maximum plantar flexion moment and the maximum dorsiflexion moment of the ankle joint increased significantly ($p<0.05$); The maximum ankle strength is significantly increased ($p<0.05$), and the minimum value decreased significantly ($p<0.05$).

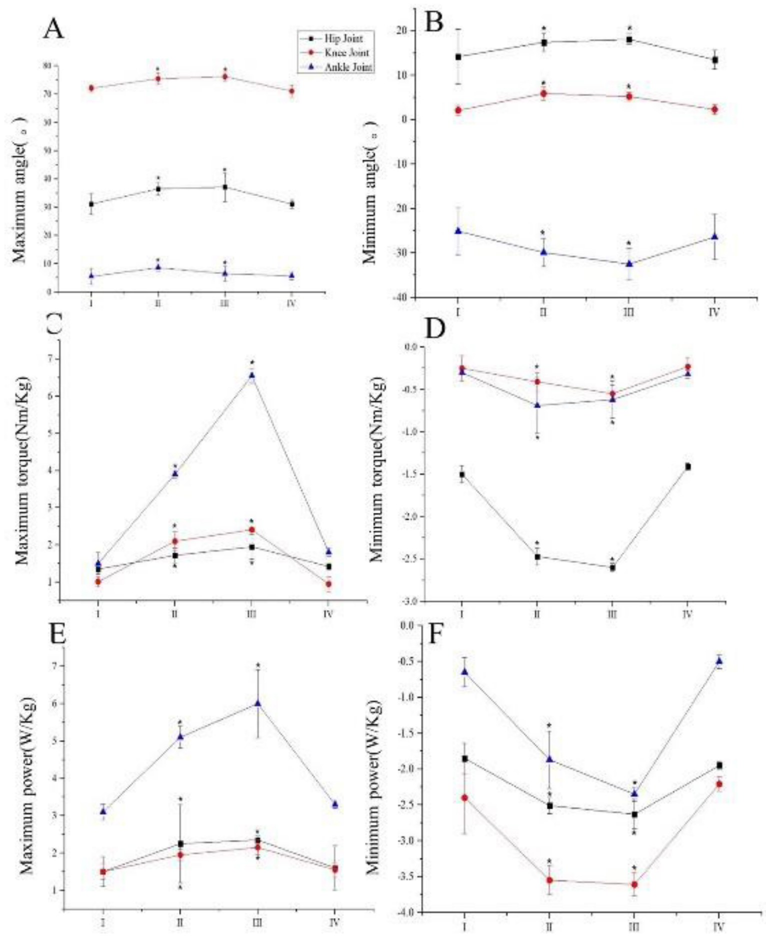

Figure 2: The effect of FMJC on the biomechanics of the unrestricted lower limb joints. A: Maximum angle, B: Minimum angle, C: Maximum torque, D: Minimum torque, E: Maximum power, F: Minimum power; Time point: I (0min Bare Foot), II(0minFMJC), III (30minFMJC), IV (Bare Foot after 30min FMJC); Compared with the time point I * p<0.05.

Kinematics and Biomechanical Parameters of the Knee Joint of the Right Lower Extremity in the case of FMJC of the Left Lower Extremity

Compared with the time node (I) 0min barefoot walking, the maximum flexion angle at the two FMJC time points were significantly increased ($p<0.05$), there are significant differences in torque, work and power ($p<0.05$), and there is a trend of joint motion compensation in the transmission of mechanical loads.

Kinematics and Dynamic Biomechanical Parameters of the Hip Joint of the Right Lower Extremity in the case of FMJC of the Left Lower Extremity

Compared with time node (I) 0min barefoot walking, the maximum angle, minimum angle, and maximum torque of the hip joint at the two FMJC time points are significantly different ($p<0.05$), and the maximum torque of the hip joint is significantly increased ($p< 0.01$), there is a compensatory trend in the transfer of mechanical load.

In summary, in the case of FMJC of the left lower extremity, the torque of the right lower extremity hip, knee and ankle joints change the same. It shows that there is joint motion compensation between the hip, knee and ankle, and the power of hip, knee, and ankle all show positive correlation changes. In the attenuation of torque compensation transmission, the ankle, knee and hip torque changes have a tendency to decrease.

The first to fifth MJs belong to the forefoot and are composed of 5 metatarsal heads and the proximal phalangeal base. Since each MJ is often flexed and extended at the same time during exercise, it is also collectively called MJ, referred to as MPJ or MTP joint. At this stage, people have begun to reexamine the role of the MJ, the second largest joint of the foot that has been neglected for a long time, in human running and jumping, including how to effectively train the MJs to improve joint energetics and muscle activation patterns, and ultimately improve athletic performance [4,12].

Dynamic Changes of the Unrestricted Hip, Knee and Ankle Joint in the Case of Short-Term Unilateral FMJ Movement Restriction

In this trail, unilateral FMJC significantly affected the biomechanical parameters of the ankle, knee, and hip joints of the unrestricted side of the lower limb when walking, but there is no significant difference in gait parameters on the unrestricted side of the lower limbs; In order to ensure the integrity of the movement of the human body, adjacent and distal joints have a compensation function [19,20]. Although short-term FMJC is only shown in the data as ankle, knee and hip joint load transfer, the knee joint load change is not obvious, but research shows that long-term knee joint load increase will greatly increase the morbidity of the knee joint [21]. Therefore, the potential risk of FMJC is not only for the contralateral ankle joint, but also for the contralateral knee joint and even the hip joint; the treatment effect of many patients with knee arthritis is not satisfactory because the function of the foot and ankle is not paid attention to. Existing research have shown that foot and ankle function have an impact on knee joint disease [22], However, the influence of FMJC is not pointed out. The results of this study proved the following hypothesis: FMJC has a potential impact on the occurrence and development of knee arthritis in the contralateral lower limb.

In the Short-Term Unilateral Movement of the FMJ is Restricted, There is Motion Compensation Transmission in the Unrestricted Side Ankle, Knee and Hip Joint

In this trail, FMJC significantly affected the biomechanical parameters (torque, power, angle, etc.) of the unrestricted side ankle joint, knee joint, and hip joint during walking, while the traditional kinematics data (such as step length, step width, pace, etc.) showed no significant changes. If one joint has disease, other adjacent joints will use motion compensation to ensure the integrity of motion [23,24].

Shortcomings and Prospects

Of course, our research still has many shortcomings. First of all, the number of our subjects is relatively small, and the accuracy of the experimental results will be affected; Secondly, the FMJC brace we use still has defects in restricting the movement and durability of the MJs, and more suitable materials can be used in the future; We have not paid attention to the impact of some movement patterns in real life scenes on FMJC, such as sprints and sudden stops, and artificial changes in a certain biomechanical factor of the MJs. For example, the position of the support point, the size of the joint activity, etc., what kind of corresponding changes will occur in the other joints of the lower limbs of the human body, and how this change will contribute to coordinated movement, etc., the exploration of this series of questions is obviously helpful to understand the movement function of the MJ itself and the possible relationship between it and the performance of the movement.

Conclusion

After the unilateral FMJ is restricted, the lower limb joints on the unrestricted side of the human body can increase the work and increase the angle of motion to compensate for the load, thereby maintaining the normal gait of the unrestricted side and reducing the load on the restricted side joint; The load compensation transmission of the lower limb joints on the unrestricted side showed a decreasing order from the ankle joint to the knee joint and then to the hip joint.

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Conflicts of Interest

The authors have no conflict of interest to declare.

References

1. Jarvis DN, Kulig K (2016) Kinematic and kinetic analyses of the toes in dance movements. J Sports Sci 34(17): 1612-1618.
2. Miller F, Arenson D, Weil LS (1977) Incongruity of the first metatarsophalangeal joint. The effect on cartilage contact surface area. J Am Podiatry Assoc 67(5): 328-333.
3. Kier R, Abrahamian H, Caminear D, Eterno R, Feldman A, *et al.* (2010) MR arthrography of the second and third metatarsophalangeal joints for the detection of tears of the plantar plate and joint capsule. AJR Am J Roentgenol 194(4): 1079-1081.
4. Allman LM, Keating SE (2000) First metatarsophalangeal joint implant as a salvage procedure. J Am Podiatr Med Assoc 90(6): 303-308.
5. Rowley KM, Shih HS, Traina K, Winder B, Mikkelsen P, *et al.* (2021) Effects of a "toes-off" modified heel raise on muscle coordination in non-dancers, dancers, and dancers with flexor hallucis longus tendinopathy. Clin Biomech (Bristol, Avon) 83: 105287.
6. Okamura K, Egawa K, Okii A, Oki S, Kanai S (2020) Intrinsic foot muscle strengthening exercises with electromyographic biofeedback achieve increased toe flexor strength in older adults: A pilot randomized controlled trial. Clin Biomech (Bristol, Avon) 80: 105187.
7. Roy JP, Stefanyshyn DJ (2006) Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. Med Sci Sports Exerc 38(3): 562-569.
8. Perry SD, Radtke A, Goodwin CR (2007) Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination. Gait Posture 25(1): 94-98.
9. Branthwaite H, Grabtree G, Chockalingam N, Greenhalgh A (2018) The Effect of Toe Flexion Exercises on Grip. J Am Podiat Med Assn 108: 355-361.
10. Day EM, Hahn ME (2019) Dynamic angular stiffness about the metatarsophalangeal joint increases with running speed. Hum Mov Sci 67: 102501.
11. Waldrop NE, 3rd (2021) Assessment and Treatment of Sports Injuries to the First Metatarsophalangeal Joint. Foot Ankle Clin 26(1): 1-12.

12. Munteanu SE, Landorf KB, McClelland JA, Roddy E, Cicuttini FE, *et al*. (2021) Shoe-stiffening inserts for first metatarsophalangeal joint osteoarthritis: a randomised trial. Osteoarthritis Cartilage 29(4): 480-490.

13. Kirane YM, Michelson JD, Sharkey NA (2008) Contribution of the flexor hallucis longus to loading of the first metatarsal and first metatarsophalangeal joint. Foot Ankle Int 29(4): 367-377.

14. Prachgosin T, Chong DYR, Leelasamran W, Smithmaitrie P, Chatpun S (2015) Medial longitudinal arch biomechanics evaluation during gait in subjects with flexible flatfoot. Acta Bioeng Biomech 17(4): 121-130.

15. Konrad A, Mocnik R, Nakamura M, Sudi K, Tilp M (2020) The Impact of a Single Stretching Session on Running Performance and Running Economy: A Scoping Review. Front Physiol 11: 630282.

16. Menz HB, Morris ME (2006) Clinical determinants of plantar forces and pressures during walking in older people. Gait Posture 24(2): 229-236.

17. Budhabhatti SP, Erdemir A, Petre M, Sferra J, Donley B, *et al*. (2007) Finite element modeling of the first ray of the foot: a tool for the design of interventions. J Biomech Eng 129(5): 750-756.

18. Xu R, Zuo H, Ji Y, Li Q, Wang Z, *et al*. (2021) Effects of Short-Term Limitation of Movement of the First Metatarsophalangeal Joint on the Biomechanics of the Ipsilateral Hip, Knee, and Ankle Joints During Walking. Med Sci Monit 27: e930081.

19. Veryha Y, Kurek J (2003) Application of joint error mutual compensation for robot end-effector pose accuracy improvement. J Intell Robot Syst 36: 315-329.

20. Yu CL, Li ZQ, Liu H (2018) Research on Gravity Compensation Algorithm of Model-free Manipulator Based on L-1-norm Convex Optimization. 2018 Ieee International Conference on Robotics and Biomimetics (Robio) 1444-1450.

21. Wang WJ, Liu F, Zhu YW, Sun MH, Qiu Y, *et al*. (2016) Sagittal alignment of the spine-pelvis-lower extremity axis in patients with severe knee osteoarthritis: A radiographic study. Bone Joint Res 5(5): 198-205.

22. Singer NV, Saunders NE, Holmes JR, Walton DM, Finney FT, *et al*. (2021) Presence of Neovascularization in Torn Plantar Plates of the Lesser Metatarsophalangeal Joints. Foot Ankle Int 42(7): 944-951.

23. Kim SH, Min BK (2020) Joint Compliance Error Compensation for Robot Manipulator Using Body Frame. Int J Precis Eng Man 21: 1017-1023.

24. Thompson MA, Gutmann A, Seegmiller J, McGowan CP (2014) The effect of stride length on the dynamics of barefoot and shod running. J Biomech 47(11): 2745-2750.