Biomechanics Analysis of the Lower Limbs in 20 Male Sprinters Using the International Society of Biomechanics Six-Degrees-of-Freedom Model and the Conventional Gait Model

Authors' Contribution:
Study Design **A**
Data Collection **B**
Statistical Analysis **C**
Data Interpretation **D**
Manuscript Preparation **E**
Literature Search **F**
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Background: This biomechanics study of the lower limbs aimed to compare the use of the International Society of Biomechanics Six-Degrees-of-Freedom (ISB-6DOF) model and the conventional gait model (CGM), formerly known as the Helen Hayes model, in 20 male sprinters who habitually used the forefoot (FF) or rearfoot (RF) strike modes.

Material/Methods: We used a motion capture system to compare the difference in lower-extremity joint mechanics between sprinters' forefoot or rearfoot strike mode during unplanned sidestepping (UPSS). Twenty elite sprinters participated in a motion capture test under 2 models. Each of the 10 participants were classified as having a habitual forefoot strike mode or rearfoot strike mode during unplanned sidestepping. Joint mechanics and gait parameters were calculated according to the designed movement.

Results: Comparison of the 2 models showed that the knee joint angles were inconsistent ($P<0.05$), highlighting the difficulty of the Helen Hayes model in anatomical recognition. The results of the 2 models show that during the unplanned sidestepping, the sprinter using the habitual rearfoot strike mode had a greater load through the knee joint ($P<0.05$). Sprinters who used the habitual forefoot strike mode experienced greater load through their ankle joints ($P<0.05$).

Conclusions: The findings from this biomechanics study showed that when compared with the ISB-6DoF model, the findings from the CGM were more reproducible for the evaluation of FF and RF strike during unplanned sidestepping.

Keywords: Ankle Joint • Athletes • Kinetics • Knee Joint

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Background

The Standardization and Terminology Committee (STC) of the International Society for Biomechanics (ISB) proposed a joint kinematics report standard based on the Joint Coordinate System (JCS), which was first proposed by Grood and Suntay in 1983 for the knee joint [1]. Three-dimensional kinematics measurement of gait is often used in clinical gait analysis, and provides key outcome measurements for gait research and clinical practice. This systematic review identified and evaluated current evidence to demonstrate the inter-session and inter-rater reliability of three-dimensional kinematic gait analysis (3DGA) data [2]. Gait analysis is usually based on markers placed at standard locations, and various arrangements have been proposed so far, but clinical use is mostly based on changes in the Helen Hayes (HH) model [3]. Because this model was developed for low-resolution imaging systems, it must be used as little as possible [4]. As a result, joint motion is only constrained by 3 rotational degrees of freedom (3DOF); for example, the definition of the thigh segment depends on the hip joint center estimated from the pelvic marker, the definition of the calf segment depends on the knee joint marker shared with the thigh and foot, and the segment definition relies on the center of the ankle joint marked from the calf. These constraints can cause errors in joint angle calculations [5].

A lot of work has been done to develop a collection that tracks each part independently [6,7]. In clinical gait analysis, as long as the relationship with the anatomical landmarks allows segmental reconstruction, more accurate tracking can be achieved by marker clusters on rigid plates [8]. To evaluate the actual application of clinical gait laboratories, we designed a 6DOF model based on the existing literature [9]. Six-degrees-of-freedom (DOF) are defined as: 3 translations (T) (Tz: axial compression, Tx: lateral shear, Ty: forward and backward shear) and 3 rotations (R) (Rz: torsional, Rx: Flexion and extension, Ry: lateral bending) [10]. This study compared the 6DOF model with the clinically used HH model in the Sprinter Unplanned Sidestepping (UPSS) campaign.

UPSS is the leading cause of non-contact anterior cruciate ligament (ACL) injury in most dynamic exercises [11,12]. An athlete's foot strike mode is closely related to the occurrence of ACL [13,14]. The general mechanical cause of ACL injury is the application of external forces that cause increased knee load and reduced muscle support [15]. Dempsey et al [16] showed that peak valgus knee joint torque can predict the incidence of ACL injury during exercise. As the existing experiment did not involve the use an effective foot contact model during the simulation [17], conclusions related to the athlete's joint kinematics and ACL injury risk were not obtained during the UPSS. In this experiment, we attempt to study the relationship between the joint dynamics and ACL injury risk of sprinters.

This biomechanics study of the lower limbs aimed to compare the use of the International Society of Biomechanics Six-Degrees-of-Freedom (ISB-6DoF)- model and the conventional gait model (CGM), formerly known as the Helen Hayes model, in 20 male sprinters who habitually used the forefoot (FF) and rearfoot (RF) strike modes. We compared the lower-extremity joint mechanics between sprinters using forefoot or rearfoot strike mode during the UPSS based on the 6DOF model and the HH model. Because different foot strike modes will lead to different parameters, such as the contact angle and contact area between the foot and the ground at different stages, we hypothesized that there are differences in knee and ankle mechanical parameters between sprinters who use habitual rearfoot (UPSS-RF) and forefoot (UPSS-FF) strike modes during the weight-bearing (WB) phase. Further, we hypothesized that sprinters using the habitual UPSS-RF strike mode would show elevated peak knee abduction torque and ACL injury risk compared with sprinters with a habitual UPSS-FF strike mode.

Material and Methods

This experiment was approved by the Ethics Committee of the Second Hospital of Jilin University. Twenty elite male sprinters participated in the study (age 21.24±1.42 years, height 1.78±0.13 meters, weight 61.94±3.12 kg). All participants provided their written informed consent before data collection. The participants were diagnosed as healthy by the team's medical staff before testing. All subjects had no history of trauma within 1 year. Each of the 10 participants were classified as having a natural habitual rearfoot (RF) or habitual forefoot (FF) strike mode (**Figure 1**) before the experiment. Participants with natural habitual rearfoot (RF) and habitual forefoot (FF) strike modes were categorized into the UPSS-RF and UPSS-FF groups, respectively.

All participants performed the 2 motion capture tests of the HH model and the 6DOF model. **Table 1** shows marker positions of the 6DOF and HH models. During the test, the athlete was asked to wear only training shorts and remain barefoot. All participants completed the experimental design of the exercise program, which included pre-planning in a random order and unplanned straight-running, crossover, and direction-changing (avoidance movement). Participants completed 5 successful tests in each exercise mission.

Kinetic evaluation was performed in a gait laboratory, using a three-dimensional gait analysis system (including a 6-camera motion analysis system and a force plate), in a blinded manner by the same assessor [18]. A 10-meter-long runway served as the patient's walking route. The digital video camera records their movements from the front, rear, left, and right sides, and the 2 sets apply the marker position and segment definitions described in **Figure 1**. The 3D motion capture system is used
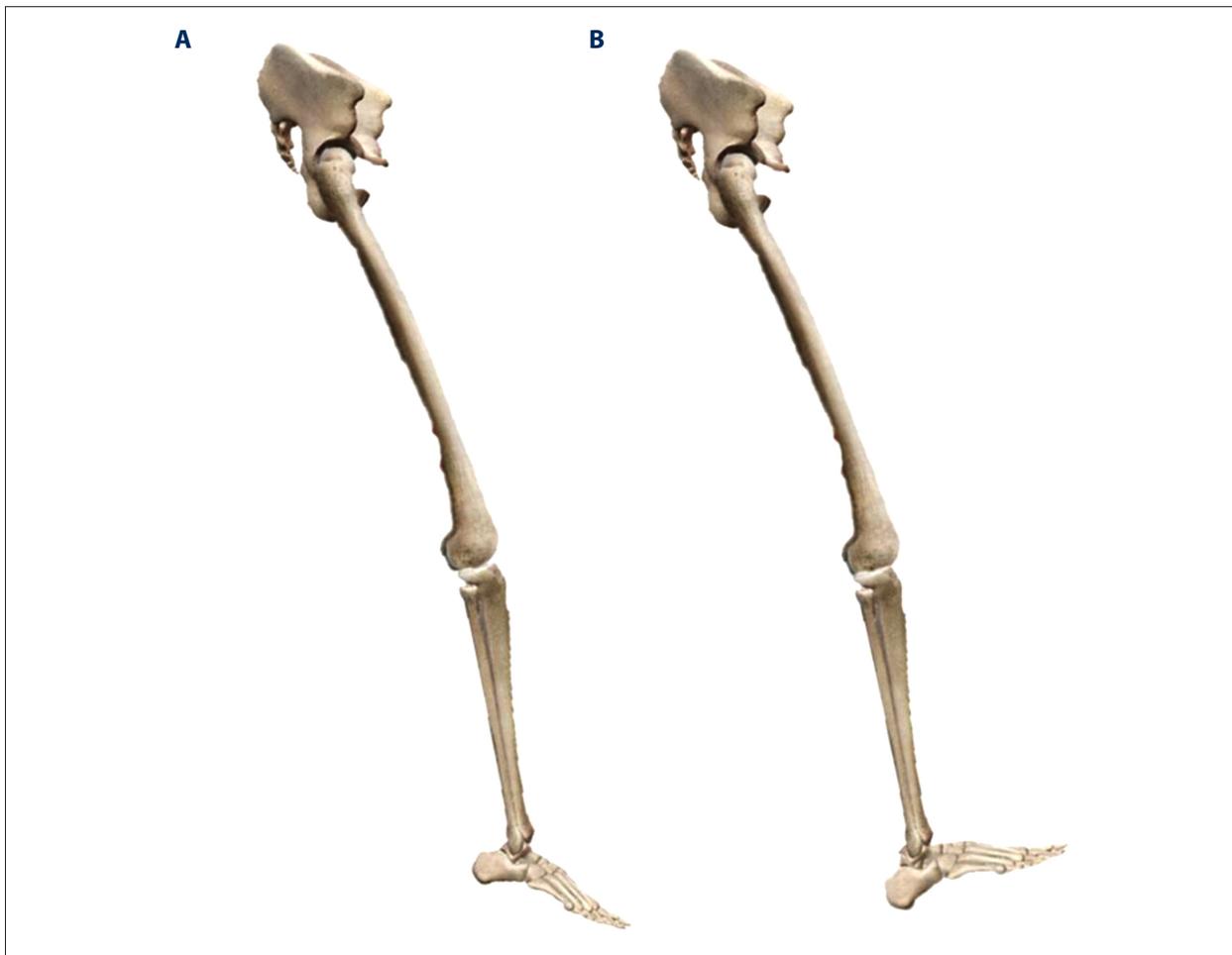
Figure 1. (**A**) Habitual forefoot (FF) strike mode, (**B**) habitual rear foot (RF) strike mode.

to capture the motion trajectory of the marker point, and the coordinates of the marker point are generated for later data processing [19]. The computer obtains the data captured by the system and performs biological model analysis. We used QT66IS and Motion Analysis processing software [20].

The independent sample t test was used to compare the speeds of the participants of UPSS-RF (4.1 ± 0.2 ms^{-1}) and UPSS-FF (4.2 ± 0.3 ms^{-1}). The results showed no significant difference ($P>0.05$). The average hip, knee, and ankle angle moments were calculated in the weight-bearing phase of the 5 repeated UPSS trials. Kinematic parameters included initial foot contact (0% posture) and range of motion (ROM) of the joint angle. Joint mechanics parameters include peak knee flexion moment and peak knee abduction torque. The differences between the 2 models and between the 2 strike modes were compared with the paired t test using SPSS 24.0 software.

Results

Comparison of the 6DOF and HH models

In the hip, knee, and ankle joints, the 6DOF model showed a large SD error, indicating a lower 6DOF repeatability. In terms of joint angle, range of motion, and moment, the 6DOF and HH models have the same trend ($P>0.05$).

Common Result Under the 2 Models

Many significant differences in lower extremity movements were observed between sprinters using the habitual UPSS-RF and UPSS-FF strike modes.

In terms of joint angle at 0% contact (**Figure 2A**), the flexion/extension angle of sprinters who are used to the UPSS-RF strike mode is significantly increased compared to that of sprinters who are used to the UPSS-FF strike mode ($P<0.05$). The absolute value of ab/adduction of UPSS-FF strike mode sprinters' joints was significantly lower ($P<0.05$)

Table 1. Marker positions of the 6DOF and HH models.

6DOF	HH	Description
Anatomical sets		
L/RPS		Left and right PSIS
	SACRUM	Mid-point on line between the PSISs
L/RLK		Most prominent point of lateral femoral epicondyle
	L/R THIGH	On line between greater trochanter and knee marker, belowe hand
L/RMK		Most prominent point of medial femoral epicondyle
	L/R KNEE	On knee joint center line
L/RMA		Most prominent point of medial malleolus
	L/R TIB	Approximately midway on line between knee and ankle markers
L/RMT1		Most medially prominent point of 1st metatarsal head
	L/R TOE	Between and 10 mm proximal to 2nd and 3rd metatarsla heads
L/RMT5		Most laterally prominent point of 5th metatarsal head (For gait event detection only)
Compuationally generated virtual landmarks		
L/R HJC		Hip joint centre calculated from functional movement recording
	L/R HIP	Hip joint centre lcations calculated with regression equations
L/R KJC		Knee joint centre half way between epicondyle markers
	L/R KNEE	Knee joint centre projectod from knee marker
L/R AJC		Ankle joint centre half way between malleoli markers
	L/R ANKLE	Ankle joint centre projected from ankle marker
PELVIS		Anatomical set plus L/R PP (markers on most superior region of iliac crest)
THIGH		Rigid cluster of four markers, placed anteriorly and proximally with under and over wrap
SHANK		Rigid cluster of four markers, placed laterally and distally with under and over wrap
FOOT		Rigid cluster of three markers, placed on superior lateral face with double sided tape

In terms of the range of joint activity during weight-bearing phase (**Figure 2B**), the plantar/dorsiflexion range of sprinters who are used to the UPSS-RF strike mode is significantly decreased compared to that of sprinters who are used to the UPSS-FF strike mode ($P<0.05$). The range of femoral activity of UPSS-RF strike mode sprinters was significantly increased ($P<0.05$).
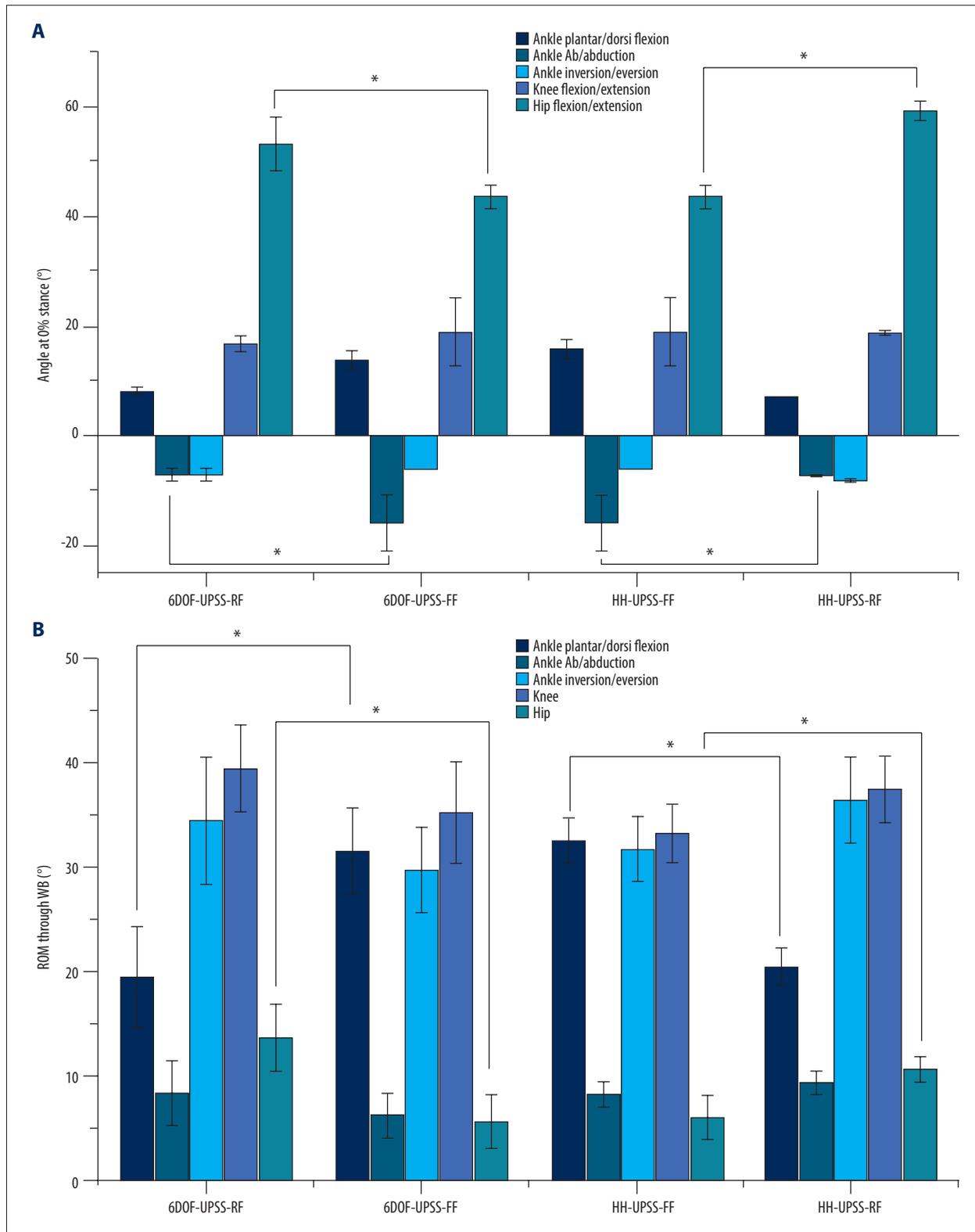
In terms of peak moment of the lower limbs (**Figure 2C**), knee flexion and knee abduction are significantly higher ($P<0.05$) in sprinters who are used to the UPSS-RF strike mode than in sprinters who are used to the UPSS-FF strike mode. However, the ankle flexion of the sprinters is obviously reduced in UPSS-FF group ($P<0.05$).

Discussion

All clinically useful evaluation tools must be repeatable. The 6DOF anatomically-based protocol enabled full 3D kinematic description of joints according to the current standard, with clinically acceptable intertrial repeatability and minimal equipment requirements, which is the same as reported by Zuk et al [21] and Collins et al [22]. In terms of repeatability, as the SD value of the HH model is generally lower than that of the 6DOF model, the HH model has better repeatability. Because of the lack of a criterion standard, the validity of the standard is difficult to assess [23]. In the absence of a criterion standard, the original 'Helen Hayes' study is widely quoted in the literature [24,25]. Unrealistic or fluctuating motion capture results may be caused by factors such as landmarks and marker misalignment or soft-tissue artifacts, but there is not enough evidence to draw conclusions. For the 6DOF model, the range of joint motion fluctuations is large; the reason for this may be the inconsistencies between subjects because of crosstalk effects [26].

For the ankle joint, the HH results have been reported to define and track the foot using only 2 markers, so the model is not strictly adapted to the foot flip/valgus [27,28]. Given this limitation, the design of the 6DOF model can make up for this shortcoming. The 6DOF model independently tracks the movement of the foot and has 3 markers [29,30], so it seems to be better than the HH model.
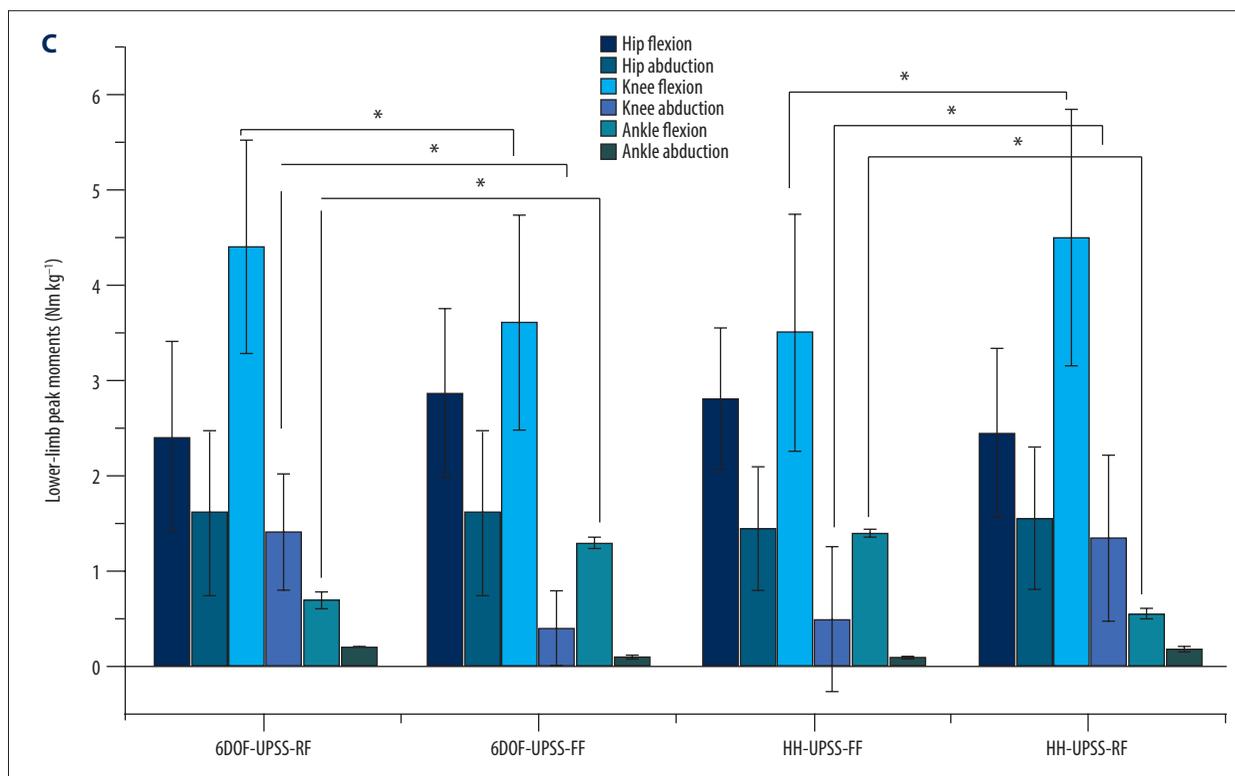
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Figure 2. Habitual UPSS-RF and UPSS-FF at the initial foot strike lower limb joint angle (**A**), the weight-bearing lower limb joint motion range (ROM) (**B**), and the peak moment of lower limb joints (**C**) in the 6DOF and HH models. * Significant difference ($P<0.05$).

The relationship between the foot strike mode, the lower-limb mechanics, and the risk of injury has been extensively studied [31-33]. Significant differences exist between athletes using habitual UPSS-FF and UPSS-RF foot strike patterns [34]. Runners with a habitual RF strike pattern have increased strength requirements for knee flexion/stretching, and runners with a habitual FF strike mode have greater need for the degree of freedom of dorsiflexion/buckling of the ankle [35,36]. Along with significantly reduced peak abduction knee torque and significantly increased peak ankle moments, sprinters who habitually use the UPSS-FF strike mode rely on more ankle support. Athletes with habitual UPSS-RF strike experience more load through their knee joints, which echoes a significant drop in the peak ankle moment and a significant increase in the peak abduction knee torque, which increases the decrease in the knee joint torque. In this strike mode, an increase in knee torque increases the risk of ACL injury, proving the hypothesis of the relationship between the UPS strike mode and ACL damage, and it also shows that sprinters using the habitual UPSS-RF strike mode show an increased peak knee abduction moment and ACL injury risk compared with sprinters using the habitual UPSS-FF strike mode.

Considered in the context of sports rehabilitation, the results of this experiment serve as technical recommendations for sprinters' foot strike pattern during the UPSS.

According to the mechanical needs of the sprinters for the ankle and knee joints, such as the knee joint dependence caused by knee joint injury, in this case, it is recommended that switching the foot strike mode may be an effective suggestion to reduce the sprinters' recovery process. There are many limitations to this experiment. The type and number of athletes determined our limitations on the research of UPSS strike mode in sports medicine. Our grouping should consider individual differences. We will increase the types and numbers of athletes in future research and improve the HH model to achieve more accurate experimental results.

Conclusions

The findings from this biomechanics study showed that, compared with the ISB-6DoF model, the findings from the CGM were more reproducible for the evaluation of FF and RF strike during unplanned sidestepping. Sprinters using the habitual UPSS-RF strike mode have increased peak knee abduction moment and ACL injury risk compared with sprinters with a habitual UPSS-FF strike mode. Changing the foot strike mode of sprinters during the UPS, depending on the knee or ankle injury of the sprinter, may be a viable protection measure.

Declaration of Figures Authenticity

All figures submitted have been created by the authors, who confirm that the images are original with no duplication and have not been previously published in whole or in part

References:

1. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion – part 1: Ankle, hip, and spine. J Biomech. 2002;35(4):543-48

2. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. Gait Posture. 2009;29(3):360-69

3. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res. 1990;8(3):383-92

4. Cappozzo A, Della Croce U, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry – part 1: Theoretical background. Gait Posture. 2005;21(2):186-96

5. Cereatti A, Camomilla V, Vannozzi G, Cappozzo A. Propagation of the hip joint centre location error to the estimate of femur vs pelvis orientation using a constrained or an unconstrained approach. J Biomech. 2007;40(6):1228-34

6. Gu YG, Gao YP. An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments. Mar Pollut Bull. 2019;146:100-5

7. Kambic RE, Roberts TJ, Gatesy SM. 3-D range of motion envelopes reveal interacting degrees of freedom in avian hind limb joints. J Anat. 2017;231(6):906-20

8. Li JS, Tsai TY, Felson DT, et al. Six degree-of-freedom knee joint kinematics in obese individuals with knee pain during gait. PLoS One. 2019;14(2): e0174663 [Erratum in: PLoS One. 2019;14(2):e0213084]

9. Hennessy D, Arauz P, Klemt C, et al. Gender influences gait asymmetry following bicruciate-retaining total knee arthroplasty. J Knee Surg. 2020;33(6):582-88

10. Guenther D, Sexton SL, Bell KM, et al. Non-uniform strain distribution in anterolateral capsule of knee: Implications for surgical repair. J Orthop Res. 2019;37(5):1025-32

11. Onushko T, Boerger T, Van Dehy J, Schmit BD. Dynamic stability and stepping strategies of young healthy adults walking on an oscillating treadmill. PLoS One. 2019;14(2):e0212207

12. Brown SR, Brughelli M, Hume PA. Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. Sports Med. 2014;44(11):1573-88

13. Stoelben KJV, Pappas E, Mota CB. Lower extremity joint moments throughout gait at two speeds more than 4 years after ACL reconstruction. Gait Posture. 2019;70:347-54

14. Minhas SV, Kester BS, Larkin KE, Hsu WK. The effect of an orthopaedic surgical procedure in the National Basketball Association. Am J Sport Med. 2016;44(4):1056-61

15. Teng PSP, Leong KF, Kong PW. Influence of foot-landing positions at initial contact on knee flexion angles for single-leg drop landings. Res Q Exercise Sport. 2020;91(2):316-25

16. Erickson LN, Lucas KCH, Davis KA, et al. Effect of blood flow restriction training on quadriceps muscle strength, morphology, physiology, and knee biomechanics before and after anterior cruciate ligament reconstruction: Protocol for a randomized clinical trial. Phys Ther. 2019;99(8):1010-19

17. Dempsey AR, Lloyd DG, Elliott BC, et al. Changing sidestep cutting technique reduces knee valgus loading. Am J Sport Med. 2009;37(11):2194-200

18. Xu R, Zuo H, Ji YB, et al. 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. 2021;27:e930081

19. Xu R, Wang Z, Ma T, et al. Effect of 3D printing individualized ankle-foot orthosis on plantar biomechanics and pain in patients with plantar fasciitis: A randomized controlled trial. Med Sci Monit. 2019;25:1392-400

20. Xu R, Wang Z, Ren Z, et al. Comparative study of the effects of customized 3D printed insole and prefabricated insole on plantar pressure and comfort in patients with symptomatic flatfoot. Med Sci Monit. 2019;25:3510-19

21. Zuk M, Pezowicz C. Kinematic analysis of a six-degrees-of-freedom model based on ISB recommendation: A repeatability analysis and comparison with conventional gait model. Appl Bionics Biomech. 2015;2015:503713

22. Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A 6 degrees-of-freedom marker set for gait analysis: Repeatability and comparison with a modified Helen Hayes set. Gait Posture. 2009;30(2):173-80

23. Lie MM, Risberg MA, Storheim K, et al. What's the rate of knee osteoarthritis 10 years after anterior cruciate ligament injury? An updated systematic review. Br J Sports Med. 2019;53(18):1162-67

24. Szczerbik E, Kalinowska M. The influence of knee marker placement error on evaluation of gait kinematic parameters. Acta Bioeng Biomech. 2011;13(3):43-46

25. Collins TD, Ghoussayni SN, Ewins DJ, Kent JA. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. Gait Posture. 2009;30(2):173-80

26. Northeast L, Gautrey CN, Bottoms L, et al. Full gait cycle analysis of lower limb and trunk kinematics and muscle activations during walking in participants with and without ankle instability. Gait Posture. 2018;64:114-18

27. Ferrari A, Benedetti MG, Pavan E, et al. Quantitative comparison of five current protocols in gait analysis. Gait Posture 2008;28(2):207-16

28. Yoshimoto K, Noguchi M, Yamada A, Nasu Y. Compensatory function of the subtalar joint for lower extremity malalignment. Adv Orthop. 2019;2019:7656878

29. Pothrat C, Authier G, Viehweger E, Rao G. Multifactorial gait analysis of children with flat foot and hind foot valgus deformity. Comput Method Biomec. 2013;16:80-81

30. Gale T, Anderst W. Asymmetry in healthy adult knee kinematics revealed through biplane radiography of the full gait cycle. J Orthop Res. 2019;37(3):609-14

31. Liu XM, Wiersma RD. Optimization based trajectory planning for real-time 6DoF robotic patient motion compensation systems. PLoS One. 2019;14(1):e0210385

32. Hamill J, Gruber AH, Derrick TR. Lower extremity joint stiffness characteristics during running with different footfall patterns. Eur J Sport Sci. 2014;14(2):130-36

33. Browne MG, Franz JR. The independent effects of speed and propulsive force on joint power generation in walking. J Biomech. 2017;55:48-55

34. Simpson JD, Stewart EM, Rendos NK, et al. Anticipating ankle inversion perturbations during a single-leg drop landing alters ankle joint and impact kinetics. Hum Movement Sci. 2019;66:22-30

35. Lee MJC, Lloyd DG, Lay BS, et al. Different visual stimuli affect muscle activation at the knee during sidestepping. J Sport Sci. 2019;37(10):1123-28

36. Okita Y, Yamasaki N, Nakamura T, et al. Intra-individual biomechanical effects of a non-microprocessor-controlled stance-yielding prosthetic knee during ramp descent in persons with unilateral transfemoral amputation. Prosthet Orthot Int. 2019;43(1):55-61