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The free moment is associated with torsion between the pelvis and the foot during gait

Takahiro Ohkawa[a,b], Tomoaki Atomi[c], Katsuya Hasegawa[b,d], Yoriko Atomi[b,*]

[a] Department of Physical Therapy, Faculty of Health Science Technology, Bunkyo Gakuin University, 1196 Kamekubo, Fujimino-shi, Saitama 356-8533, Japan
[b] Department of Material Health Science, Faculty and Graduate School of Engineering, Tokyo University of Agriculture and Technology, 204 Research Center for Science and Technology, Koganei-shi, Tokyo 184-8588, Japan
[c] Department of Physical Therapy, Faculty of Medical Sciences, Teikyo University of Science, 2525 Yatsuzawa, Uenohara-shi, Yamanashi 409-0193, Japan
[d] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara-shi, Kanagawa 252-5210, Japan

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ABSTRACT

Background: During walking, the friction between the foot and the ground surface causes a free moment (FM), which influences the torsional stress on the lower extremity. However, few studies have investigated the FM during natural walking. The main aim of this study was to examine the relationship between the FM and the absolute and relative rotation angles of the foot and pelvis.

Methods: The rotation angles of foot and pelvic were measured in 18 healthy men using a motion capture system. Rotation angles were measured in absolute and relative coordinates as well as in reference to the line connecting the center of pressure (CoP) line under the right and left feet to evaluate the effects of the opposite lower limb on the FM. The absolute and relative rotation angles of the foot and pelvis were entered into forced-entry linear regression models to evaluate the influence on the FM.

Findings: Only the relative angle of rotation between the foot and pelvis could explain the prediction equations significantly. In the Pearson's product-moment correlation coefficient, the rotation angles of the foot and pelvis defined using the bilateral CoP points had not significantly correlated with FM. No joint rotation movement was correlated with FM.

Interpretation: : The torsion of the entire lower extremity should be performed principally through hip internal rotation. When evaluating the FM as a torsional stress, focusing on the rotation of the entire lower extremity, rather than on one segment, is beneficial.

1. Introduction

Significant relationships between some arthropathies and joint rotation of lower limb during gait have been reported [1,2]. In addition, the characteristic of the torsional profile of arthropathies and cerebral palsy has been revealed [3–5]. Although understanding the torsional stress on the lower limb bones is important, the etiology of abnormal deformation has not been clarified. It is generally thought that torsional stress affects bone morphology and deformation [6]. Studies on the strain generated on the lower limb bone during gait have been conducted [7,8]. However, such in vivo studies need invasive surgery of subjects, which adds to their physical burden.

Recently, the free moment (FM) attracted attention as an index of torsional stress in the lower limbs, and it has been reported to be related with tibial stress fracture in distance runners [9]. Moreover, Yang et al. [10] reported that the FM was related to greater torsional deformity of the tibia than the vertical ground reaction force (GRF) during gait. The plantar surface is a unique plane that contacts the floor and is a site where friction develops to propel the whole body during biped locomotion. Torsional stress is generated in the lower limb during bipedal walking, which performs the rotational motion in the stance phase [11]. Consequently, excessive stress during gait could have a harmful effect on the lower limb structure and on joint motion [6].

The FM, which is caused by friction, is defined as the reaction force to the torsional moment applied by the subject about the vertical axis located at the center of pressure (CoP) coordinates [12] (Fig. 1a). Although the FM does not directly quantify the torque of the lower limb, it could be used as a meaningful index of the torsional stress applied on the lower limbs during gait. Hence, it is important to clarify the relationships between the FM and the characteristics of gait to understand

* Corresponding author at: Department of Material Health Science, Faculty and Graduate School of Engineering, Tokyo University of Agriculture and Technology, 204 Research Center for Science and Technology, Koganei-shi, Tokyo 184-8588, Japan.
E-mail addresses: tohkawa@bgu.ac.jp (T. Ohkawa), atomi@ntu.ac.jp (T. Atomi), hasegawa@keisoku.jaxa.jp (K. Hasegawa), yatomi@cc.tuat.ac.jp (Y. Atomi).

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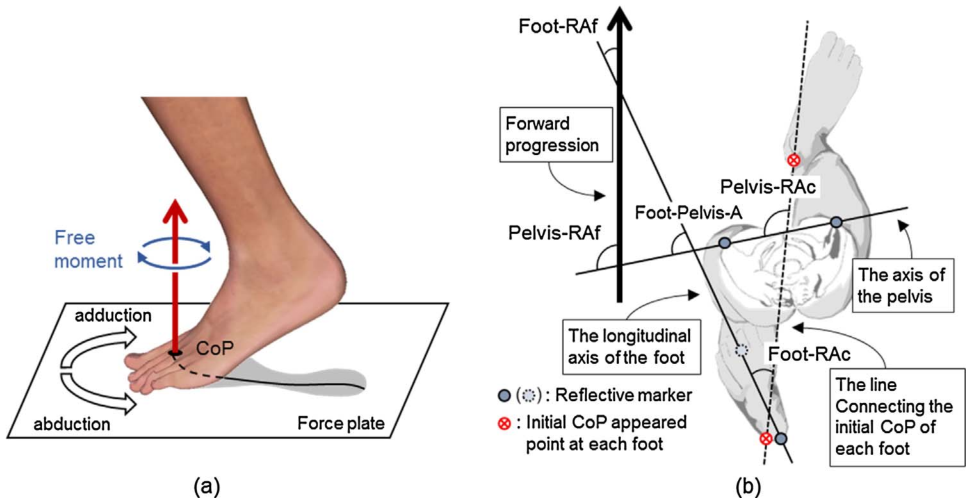

Fig. 1. Schematic representations of the free moment (a) and measured kinematic variables (b) during the stance phase.
The red arrow indicates the vertical ground reaction force. The positive/negative (clockwise/counter-clockwise) free moment value represents the friction force resisting foot abduction/adduction in this study. It is customary to use "abduction/adduction"; note that the center of rotation of the foot does not necessarily coincide with the location of the center of pressure (CoP).
Foot-RAf, foot rotation angle in the line of forward progression; Foot-RAc, foot rotation angle with respect to the line connecting the initial CoP under each foot; Pelvis-RAf, pelvic rotation angle in the forward progression; Pelvis-RAc, pelvic rotation angle with respect to the line connecting the initial CoP under each foot; Foot-Pelvis-A, relative angle of rotation between the foot and the pelvis.

stressful walking on the transverse plane.

Since Schoenhaus et al. [13] pointed out a relationship between the FM and the function of the foot during gait, a few studies have demonstrated that the peak FM (PFM) can be increased by restricting arm swing [14] or by intentionally rotating the foot externally [15] during gait. However, these findings are difficult to apply clinically, as they are based on unnatural walking patterns.

Almosnino et al. [15] reported a slight correlation between the FM and absolute foot rotation angle in three conditions (natural, internal, and external rotation position). Moreover, they reported a moderate correlation ($r = 0.65$) between the relative angle at which the foot rotation angle was intentionally changed from natural walking and the PFM. From these findings, it is conceivable that foot angle is a significant factor affecting FM. The foot rotation angle is likely to be related to diseases of the lower limbs [16] and should be determined based not only on the rotation of the ankle joint but also on the internal-external rotation of the hip joint [17]. Furthermore, the pelvis rotates slightly on the transverse plane due to the rotation at the hip joint during normal walking. Based on the evidence presented above, we hypothesized that pelvic rotation and/or torsion of the entire lower limb would further influence the magnitude of the FM during gait.

In addition, Li et al. [14] reported that the FM reaches a peak at approximately the double-support phase. Hence, the location of both the left and right lower limbs needs to be considered, rather than focusing only on the supporting limb. Therefore, the primary purpose of this study was to clarify the influence of the foot rotation angle, the pelvic rotation angle, and the relative angle of rotation between the foot and the pelvis as torsion of the entire lower limb on the magnitude of FM during natural walking. We further examined the effect of bilateral lower limbs on the aforementioned relationships using bilateral CoP coordinates and relationships between the FM and joint rotation of the lower limb.

2. Methods

2.1. Participants

We recruited participants through an advertisement at the Physical Therapy Department of our institution. Participants had to be healthy, which was confirmed by a brief self-report interview, and had to provide informed consent. The exclusion criterion was history of orthopedic or neurological disorders in the lower limbs that could interfere with gait. The methods of our study were approved by the research ethics board of our institution.

2.2. Experimental procedure

Participants walked barefoot at a self-selected speed along a walkway of approximately 9 m. Sufficient practice trials were done to ensure proper foot placement on the force plate, with three successful trials of foot contact with the force plate used for analysis. Kinematic and force plate data were collected with an eight-camera, three-dimensional motion capture system (VICON Nexus; Vicon Motion Systems Ltd., Oxford, UK) and six force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Force plate and motion data were captured at a sampling rate of 100 Hz and then low-pass filtered at a cut-off frequency of 6 and 18 Hz, respectively. Thirty-five reflective markers were attached to anatomical landmarks following the Vicon Plug-in-Gait marker placement protocol. The stance phase was identified using the vertical GRF with a threshold of 10 N. The FM was computed using the following equation [18]:

$$FM = Mz - Fy(CoPx) + Fx(CoPy)$$

where Mz denotes the horizontal moment at the center of force plate, Fx and Fy denote the medial-lateral and anterior-posterior components of the GRF, respectively, and the $CoPx$ and $CoPy$ are the medial-lateral and anterior-posterior components of the CoP on the force plate, respectively. The positive/negative (clockwise/counterclockwise) FM value represents the friction force resisting the abduction/adduction of the left foot in this study.

Previous studies have normalized the FM to a physical parameter, typically body weight (BW) or BW × height or leg length [9,14,19]. However, there is no consensus regarding the appropriate normalization of the FM. Wannop et al. [20] reported that normalization of the FM to BW could decrease between-subject variability. Accordingly, we normalized the FM to BW in our analysis. The force plate data were normalized to 101 data points for between-subject comparisons of the stance phase. The impulse of FM (FMimp) was calculated as an index of accumulated torsional stress, which is the area under the absolute FM stance curve.

2.3. Definition of the rotation angle of the foot and the pelvis

The peak internal and external rotation angles of the hip, knee, and ankle during stance phase were calculated using the Vicon Clinical Manager software. In addition to these angles, the rotation angle of the foot and pelvis were defined as follows (Fig. 1b). The longitudinal axis of the foot was defined as a line connecting the marker on the heel and the marker on the head of the second metatarsal. The axis of the pelvis was defined as the line connecting the markers affixed, bilaterally, to the anterior superior iliac spines. The foot rotation angle in the forward