



Original Article

Kinetic analysis of tandem gait on a sine-wave-shaped walkway

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Abstract. [Purpose] The purpose of this study was to ascertain the kinetic characteristics on a horizontal plane, including knee joint rotation, when performing tandem gait on a sine-wave walkway. [Participants and Methods] The participants were 10 healthy adults. The movement task included tandem gait on a sine-wave walkway. The instruments used were an electromyograph and a three-dimensional motion analysis system. Regarding data analysis, we determined the knee joint rotation angle and muscle activity of the biceps femoris and semitendinosus muscle. [Results] The knee joint rotation angle range was $48.1 \pm 6.7^\circ$. Two strategies were confirmed with regard to the direction of knee joint rotation: a case in which the agonist muscle acts actively and a case in which the antagonist muscle acts passively. [Conclusion] It has been suggested that the knee joint rotational angle and muscular activity of the rotator muscle group are important for tandem gait on a sine-wave-shaped walking path.

Key words: Sine wave walkway, Tandem gait, Knee joint rotation

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INTRODUCTION

Lower leg rotation function (lower leg rotation: rotation of the lower leg relative to the femur=knee joint rotation) is important. In a clinical setting, evaluation and treatment have been developed for osteoarthritis patients, ACL-injury patients, and others who are strongly affected by knee joint rotation function. Particularly, many people who desire high performance, including ACL-injury patients, often wish to enhance leisure activities and return to sports, and also to have the opportunity to examine knee joint rotation function specifically in step movements (crossover steps, side steps, etc.)¹⁻⁴⁾. Although its importance is recognized for evaluation of the knee joint rotation function, earlier research has not led to evaluation and treatment that can be used easily in clinical situations. One must rely currently on subjective evaluation and treatment. Therefore, we have been assessing evaluation and treatment specifically related to knee joint rotation function. Change of direction is one action that is done frequently in sports and daily life¹⁾. Rotational movement of the knee joint under a loaded condition plays an important role for smooth change of direction. During physical exertion, the distance of a line of action of gravity and the floor reaction force produces a moment arm. We use it effectively when starting and braking. Although such a mechanism is used for motions accompanying movement while resisting gravity, e.g., walking, control by muscle torque is regarded as important for rotational movement on the horizontal plane such as a change of direction with a standing position. Muscle torque referred to in this paper includes torque developed by elastic tension by soft tissue. However, a method for evaluating a change of direction in the horizontal direction has not been developed to date^{6, 7)}. Therefore, a method must be developed to allow easy evaluation in a clinical environment.

To identify motion dynamics features on the horizontal plane, we specifically examined the tandem gait on a sine-wave-

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shaped walking path after producing such a walking path (Fig. 1). We conducted motion dynamic analysis of each body segment, particularly knee joint rotational movement, at a change of direction for tandem gait on a sine-wave-shaped walking path⁸⁾. In the experiment, the body trunk rotation angle was 23.3°, the hip joint rotation angle was 53.3°, and the knee joint rotation angle was 47.3°, whereas the knee joint rotation angle is similar to the value used in earlier studies^{9–11)}. We confirmed intriguing results related to the relation of each body segment angle. At the change of direction, fundamentally, when the hip joint took an internal rotation position, the knee joint took an external rotation position. In contrast, when the hip joint takes an external rotation position, the knee joint takes an internal rotation position. During normal natural walking, each adjoining body segment performs rotational movement in a reverse direction to generate torque, controlling exertion and thereby ensuring stabilization of motion (net torque)¹²⁾. From the same perspective, our previous study also presented the possibility that the hip joint controls motions by performing internal rotational movement for knee joint external rotational movement. In other words, for the tandem gait on a sine-wave-shaped walking path, rotation of lower extremity limb joints for cancellation of kinetic momentum is important. However, it remains unknown whether control by knee joint rotational movements is based either on muscular tension or inertia force. Therefore, our objective is to identify the following three tasks presented below. The first is a relation of muscular activities under a loaded condition between knee joint rotational movement, and the long head of the biceps femoris muscle and musculus semitendinosus. The second is a relation of muscular activities between knee joint rotational movement and the long head of the biceps femoris muscle and musculus semitendinosus accompanied by loads toward the anterior lower extremity in the tandem foot position. The third is a relation with muscular activities between knee joint rotational movement and the long head of the biceps femoris muscle and musculus semitendinosus when tandem gait is used while walking along a sine-wave-shaped walking path.

PARTICIPANTS AND METHODS

In Experiment 1, five healthy adults (age, 24.2 ± 4.7 years old; height, 166.6 ± 5.7 cm; weight, 60.4 ± 10.2 kg; BMI, 21.7 ± 2.7 kg/cm²) participated. In Experiment 2, five healthy adults (age, 24.6 ± 4.3 years old; height, 166.4 ± 5.7 cm; weight, 59.0 ± 8.4 kg; BMI, 21.2 ± 1.7 kg/cm²) participated. In Experiment 3, ten healthy adults (age, 22.8 ± 3.7 years old; height, 169.1 ± 4.5 cm; weight, 63.0 ± 5.1 kg; BMI, 22.0 ± 1.0 kg/cm²) participated. The pivoting foot was defined as the foot opposite to the one that kicks a ball. All participants used the left foot as the pivoting foot. Before the experiment, all participants were confirmed to be free from any disorder that restricts walking and which affects the balance function such as central nervous abnormality, orthopedic problems, visual disability, and vestibular function disorder. In addition, to minimize artifacts caused by soft tissue to the greatest degree possible, participants who fundamentally fall under normal BMI category were selected. Research contents were fully explained to the participants. Then their written consent was obtained. This research was approved by the Research ethical committee, Tohoku Bunka Gakuen University (Approval No.: Bundai Rin 15-33).

In Experiment 1, changes in knee joint rotational angle and muscular activity under a load were measured. Electromyograph (SYNAACT; NEC Corp., Tokyo, Japan), 3D-motion analyzer (LOCUS 3D MA-5000; Anima Corp., Tokyo, Japan), and six cameras were used for measurements. Sampling frequencies were, respectively, 1,000 Hz and 150 Hz. First, for the left long head of the biceps femoris muscle and left semitendinosus muscle, which are muscles used in the experiments, the area around which electromyographs are pasted was shaved and the cuticle of the skin was removed using sandpaper (Trace prep; 3 M Inc., St. Paul, MN, USA). Then an electrode was pasted according to SENIAM guideline¹³⁾. The distance between electrodes was set to 2.0 cm along the belly of the muscle from crosstalk viewpoints. Lead wires were secured using tape to prevent motion artifacts. A marker was pasted at a total of five locations of top of the head, two at the left outer epicondyle (hereinafter designated as a two-point marker on the thigh) and two at left lateral malleolus (hereinafter designated as a two-point marker on the shin) (Fig. 2). Markers pasted on the left outer epicondyle and left outer lateral malleolus were located at 1.5 cm and 10.0 cm from the respective bone indexes. A two-point marker on the thigh and two-point marker on the shin were pasted at a seated posture with a foot angle of 0°. In this case, influences of intestinal muscle ligament accompanied by knee joint bending and stretching were confirmed as minimal. At the time of measurement, to maintain balance, the upright position while the distal foot of the dominant foot touched the floor surface was defined as the starting foot position.

The following four tasks were performed after a sound signal was given. The tasks are from the knee joint neutral to

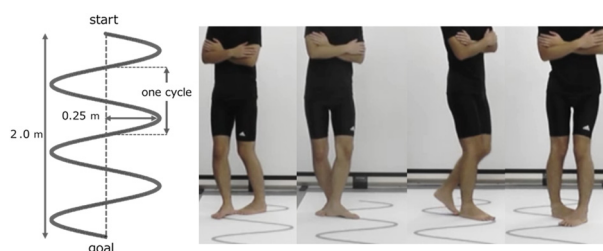


Fig. 1. Tandem gait on a sine wave walkway.

external rotation, from neutral to internal rotation, from external rotation to internal rotation, and from internal rotation to external rotation. No limitation was used for the knee joint bending angle because of knee joint rotation.

Regarding data analysis, the knee joint rotational angle and electromyogram data were subjected to resampling. Time series data were expressed in the form of a polygonal line graph. For calculation of the knee joint rotational angle, the angle formed by the line connecting the two-point marker on the thigh and the line connecting the shin and two-point marker were used. For the knee joint rotational angle, the intermediate position of the thigh and lower thigh in a seated posture was defined as 0°. The angle formed by the line connecting the thigh inner epicondyle and outer epicondyle protrusion and the horizontal line was used as the representative value.

In Experiment 2, muscular activities were measured relative to the change of direction with knee joint external rotation with a lower extremity loaded posture (hereinafter designated as knee-in) and change of direction with knee joint internal rotation (hereinafter designated as knee-out), which were observed for the change of direction with the left pivoting foot. Here, the position without knee joint rotation is defined as knee-neutral. The position of the change of direction with knee joint external rotation is defined as knee-in. The position of the change of direction with the knee joint internal rotation is defined as knee-out (Fig. 3). Two measurements of a reaction force meter (MG-1090; Anima Corp.) and an electromyograph were used, with respective sampling frequencies of 150 Hz and 1,000 Hz. An electrode was pasted to the left long head of the biceps femoris muscle and left musculus semitendinosus, which are the muscles to be tested. Next, a tandem posture across two floor reaction meters with the lower left extremity put forward was used. In this case, no load was applied to the forward lower left extremity throughout the experiment. The load level was confirmed by a vertical direction value. After a sound signal was given, each task was conducted and returned to the starting position. The measurement ended when the lower left extremity became unloaded.

For data analysis, floor reaction data and electromyogram data were subjected to resampling and time series floor reaction data in the vertical direction of the lower left extremity. Time series activity data of the long head of the biceps femoris muscle and musculus semitendinosus were expressed in the form of a polygonal line graph.

For Experiment 3, an electromyograph, 3D motion analyzer, and six cameras were used. Sampling frequencies were, respectively, 1,000 Hz and 150 Hz. First, an electrode and five markers were pasted in a manner similar to that used for Experiment 1. Next, to judge the loaded phase of the lower left extremity, a foot switch was pasted to the left heel and between the left first metatarsal bone and the left second metatarsal bone. The starting position was a standing position arm in arm at anterior chest. After a sound signal was given, tandem gait was started on the sine-wave-shaped walking path. The experiment ended when both feet passed the goal line. For execution of the task, three interruption rules were set: when crossed arms are released, when a foot leaves the walking path, and when one side heel and another side distal foot are not grounded. When any of the above was detected, the measurement task was performed again.

For data analyses, for the 2.0 m walking path, one cycle of electromyogram data and one of coordinate data were used. The electromyogram data and knee joint rotational angle were subjected to resampling and were used as time series data. In addition, the loaded phase of the lower left extremity was identified from changes in voltage by way of the foot switch. An original program produced using MATLAB® (The MathWorks Inc.) was used for data processing.

RESULTS

Figure 4 is a typical graph presenting changes in knee joint angle and muscular activities. Agonist muscle exhibited peculiar muscular activities in the knee joint motion direction in four tasks.

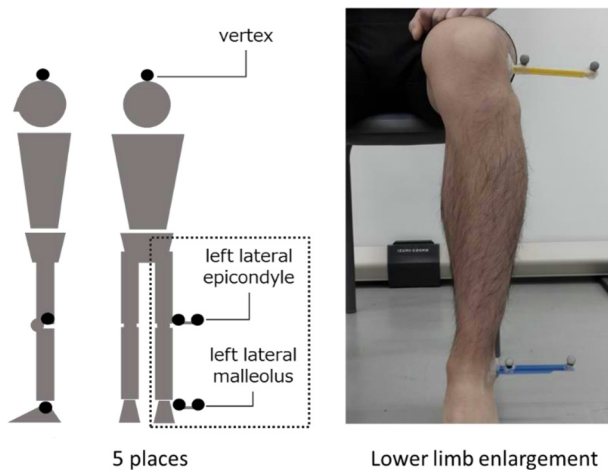


Fig. 2. Marker position.

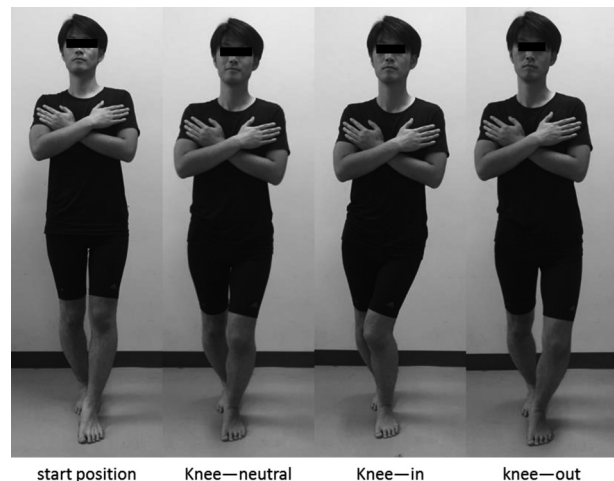


Fig. 3. Three types of operating tasks.

Figure 5 shows time series muscular activities of knee-neutral, knee-in, and knee-out. With knee-neutral, the long head of the biceps femoris muscle and semitendinosus muscle showed similar muscular activity. With knee-in, specific muscular activity by long head of the biceps femoris muscle synchronized with the increase in vertical components of floor reaction was recognized. Similarly, the semitendinosus muscle showed specific activity in knee-out. Figure 6 shows relations between changes in knee joint rotational angle and changes in each muscular activity of representative examples. The heavy line shown on the horizontal axis of the graph represents the loaded phase. Two loaded phases at intermediate positions are changes of direction where the lower left extremity is used as the pivoting foot. Although time series variation differs because of different foot lengths, an almost common relation was confirmed. Two strategies were confirmed with respect to the direction of motion of knee joint rotation; a case in which agonist muscle acts actively and a case in which antagonist muscle acts. However, in some cases, the long head of the biceps femoris muscle and semitendinosus muscle performed similar muscular activities.

Table 1 presents angular changes in the knee joint external rotation direction and those in the knee joint internal rotation direction. Results which coincide with the angular range found in an earlier study were recognized⁴⁻⁷.

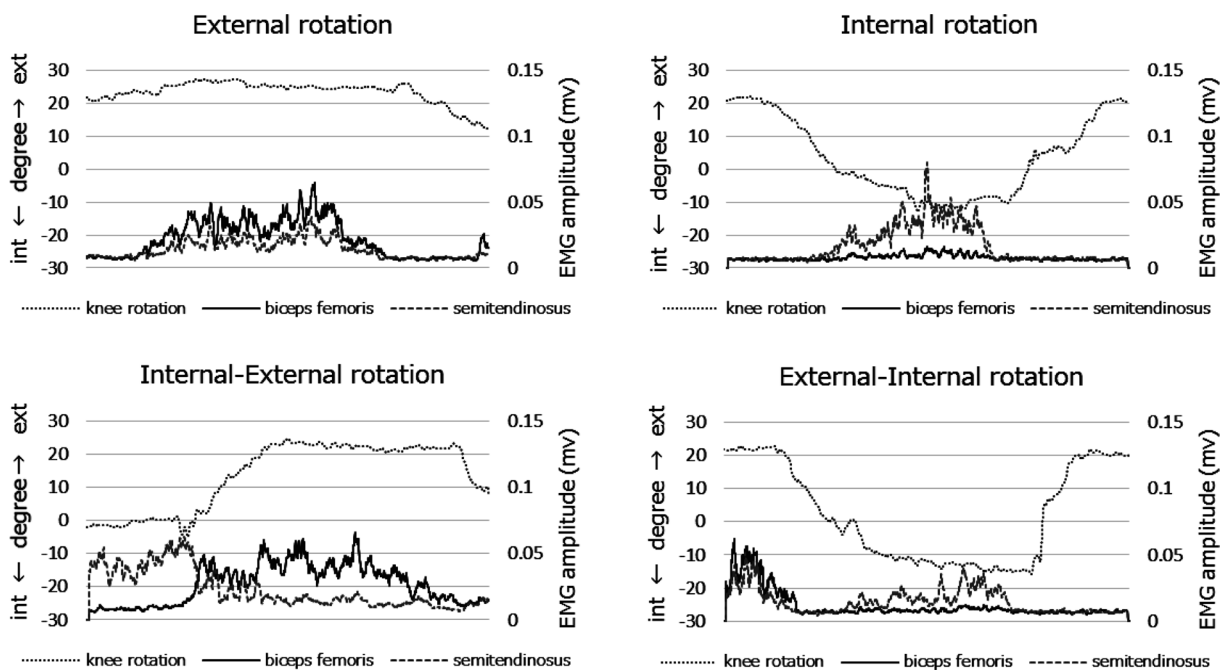


Fig. 4. The muscle activity and knee joint angle during four tasks.

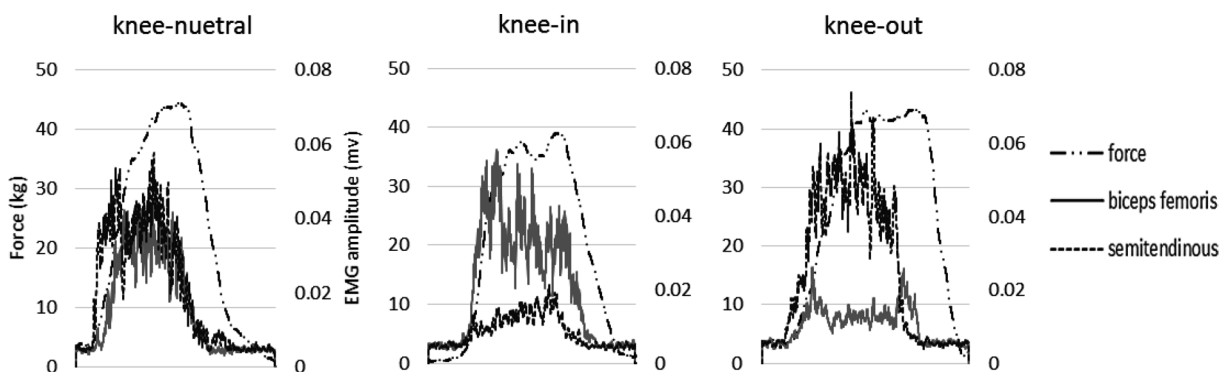


Fig. 5. The muscle activity and floor reaction force during three tasks.

DISCUSSION

It is considered that knee joint rotational movement under load is important for a smooth change of direction. For rotational motion on the horizontal plane such as change of direction with a standing position, control by muscle torque is important. However, no evaluation method is available at present. A method that allows easy evaluation at the clinical site is desired. Therefore, we produced a sine-wave-shaped walking path and attempted to identify the relation between knee joint rotational movement, and the long head of the biceps femoris muscle and semitendinosus muscle while performing tandem gait on that walking path.

In Experiment 1, whether the agonist muscle exhibits specific muscular activity in the joint motion direction in the knee joint rotational movement with loaded lower extremity was checked. As a result, specific muscular activity by agonist muscle was noticed in the joint movement direction. In Experiment 2, the floor reaction force and muscular activity were measured using three postures expected in the change of direction motion where the lower left extremity acts as the pivoting foot. As a result, for knee-neutral, the long head of the biceps femoris muscle and semitendinosus muscle exhibited similar muscular activity to that of the vertical component of floor reaction force increased. With knee-in and knee-out, specific muscular activity of the agonist muscle was noticed as if synchronized with an increase in the vertical component of the floor reaction force. In general, with knee joint rotational movement, internal rotation occurs when the inner hamstring solely contracts. External rotation occurs when the outer hamstring contracts. Reportedly^{14, 15)}, on such occasions, the contribution to rotational movement by the hamstring changes according to the stance of the knee joint; also, the moment arm of long head of the biceps femoris muscle and semitendinosus muscle is lengthened. Another study¹⁶⁾ reports that although the optimum moment arm of the hamstring is determined by the knee flexion angle, the influence by muscle length rather than the moment arm is considerable. Reportedly streamlined muscular activity by the hamstring was not noticed with internal rotation and external

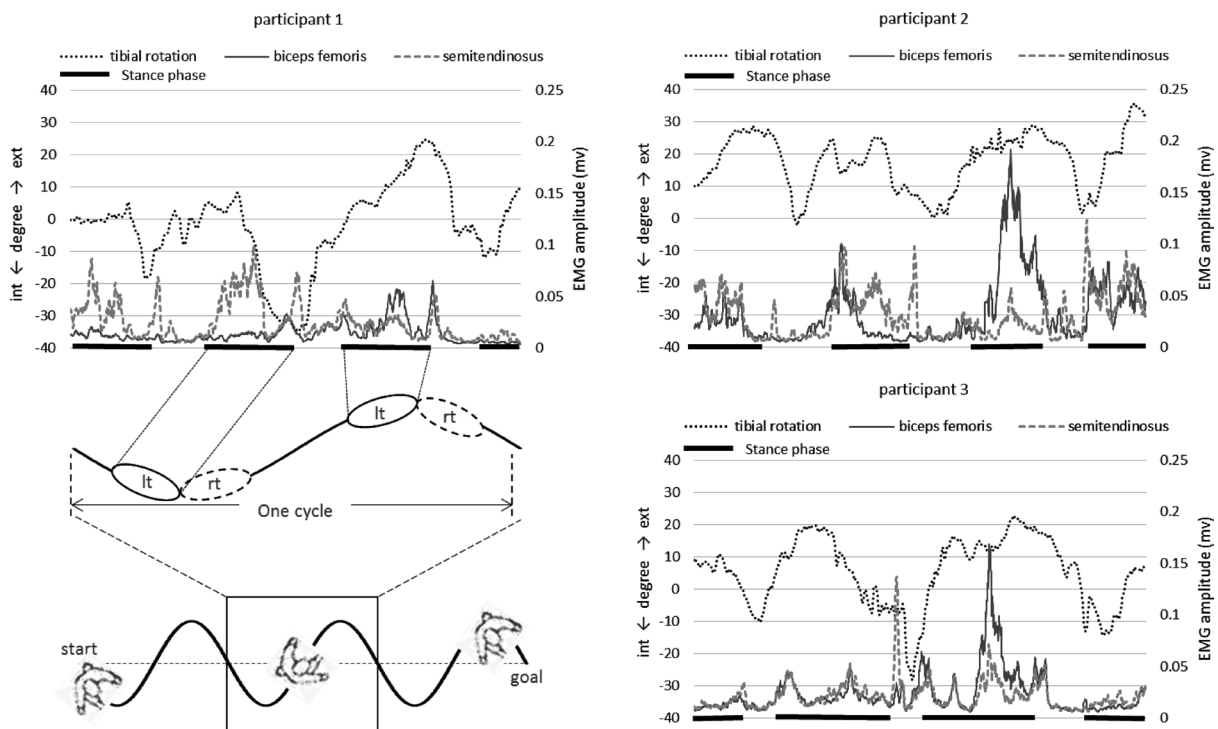


Fig. 6. Temporal sequence data of muscle activity and knee rotation angle.

Table 1. Segment angle

	Angular change to external rotation	Angular change to internal rotation	Range
Knee rotation (°)	28.3 ± 8.4	19.7 ± 12.2	48.1 ± 6.7

rotation of the knee joint with the absence of knee joint bending¹⁷). However, many of these earlier studies were conducted under no load^{18–20} or when using a test body. Therefore, it remains doubtful whether the same results are obtainable under a loaded condition.

The current study was conducted under a loaded condition while the foot position was fixed, which showed specific muscular activity in the agonist muscle at internal and external rotation with the knee joint bent position. This result resembles those presented in earlier reports. Moreover, this result suggests that the knee joint rotator muscle group acts specifically to cause physical motion such as knee-in and knee-out. Furthermore, the knee joint rotational angle and muscular activity showed a nearly uniform relation among participants. In this relation, two strategies are recognized with regard to the direction of motion of knee joint rotation. One is that agonist muscle exhibits specific activity; the other is that antagonist muscle exhibits activity. This fact is noteworthy when discussing controls on the horizontal plane.

Regarding specific muscular activity of agonist muscle with regard to the direction of motion, the results of Experiments 1 and 2 show that the knee joint rotational motion required for change of direction is realized. Results obtained from the current study, in which antagonist muscle exhibited active muscular activity, are similar to those reported by Mann. They analyzed muscular activity of the musculus popliteus when body trunk external rotation was performed under a loaded condition with the foot region fixed. Their results show that the musculus popliteus, the knee joint medial rotator, exhibited active muscular activity²¹); that indicates the possibility that, for momentum in the direction of movement, movement in the direction opposite to the direction of movement to cancel that momentum is created, thereby adjusting movements. They suggest that controls of rotational motion on the horizontal plane are made by muscular torque rather than by controls using rotational movement by the distance of the line action of gravity and the floor reaction force. Regarding similar variation by the long head of the biceps femoris muscle and semitendinosus muscle, it is unlikely that a knee joint rotator muscle group is actively influencing the change of direction. Rather, it seems probable that action with fixed knee joint and action by elastic tension is caused by soft tissues.

Regarding the change of direction, steps based primarily on side step and cross step have attracted attention^{7, 22, 23}). Additionally, it has been suggested that, for tandem gait on the sine-wave-shaped walking path, the knee joint rotational angle⁸) and muscular activity of rotator muscle group are important. In other words, for change of direction, the muscular tension of the agonist muscle and the antagonist muscle are important, as is the inertial force. For example, when execution of motion is difficult even when there is no difficulty in the range of joint movement, the functional loss of the knee joint rotator muscle group is regarded as one cause, which suggests that the tasks examined in this study are useful for the evaluation of lower thigh rotational function. However, before it is used as a convenient evaluation method for clinical use, correlation with external criteria that more faithfully reflect the properties of knee joint rotational motion should be verified. At present, no clear evaluation method exists with regard to these external criteria. However, we have identified that, on one knee position, a sophisticated balance issue is based on lower thigh rotational motion for postural maintenance^{24–26}). Therefore, we infer that it is useful to investigate the correlation of tandem gait on a sine-wave-shaped walking path with external criteria as one knee position issue. We intend to accumulate data from healthy adults to promote verification of the adequacy related to the criteria.

Conflict of interest

None.

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