



Original Article

Particular protrusion perception arising from plantar sensory input and task guidance enhances lower limb joint dynamics during gait

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Abstract. [Purpose] To assess the influence of plantar sensory input and task guidance produced by a protrusion on lower limb joint dynamics during gait by changes in muscle activity and two-dimensional motion analysis. The protrusion seals on the soles of the feet, named “Perceptual Stimulus Protrusion” were used in this study. [Participants and Methods] In this study, 40 and 42 healthy adults were recruited for muscle activity and two-dimensional analysis, respectively. In addition to walking without perceptual stimulus protrusion (“Control” condition), the testing conditions included attachment of the protrusion to the heel (“Heel Condition”) and the hallucal (“Hallucal Condition”). As task guidance, participants were orally instructed how to walk for each conditions. The muscle activities of the rectus femoris, vastus medialis, tibialis anterior, and medial head of the gastrocnemius were measured. The two-dimensional analysis was compared with the angle of ankle dorsiflexion and plantarflexion, the toe height during the swing phase between the test conditions, respectively. [Results] In the Heel Condition, the tibialis anterior and vastus medialis activity in the stance and swing phases, toe height, and angle of ankle dorsiflexion and plantarflexion increased. In the Hallucal Condition, tibialis anterior activity during the stance and swing phases, gastrocnemius activity during the stance phase, toe height, and angle of ankle plantarflexion increased. [Conclusion] Plantar sensory input and task guidance using perceptual stimulus protrusion influences active motion control. Therefore, the application of this procedure can be expected to support motion guidance, such as gait and load practice.

Key words: Plantar perception of protrusion, Enhanced lower limb dynamics, Muscle activity

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INTRODUCTION

Rehabilitative therapies can be divided into an external and internal approach. Many types of therapeutic shoe insoles, a type of orthotic treatment used in rehabilitation therapy, have externally assisted the mechanical functions of the foot by correcting the static and dynamic alignment, and body weight distribution^{1, 2)}. Meanwhile, in motion guidance programs during a rehabilitation therapy, various approaches are considered to internally improve the participant’s capacity to adapt. The problem-oriented³⁾ and system-based approaches⁴⁾ are representative methods, and having participants engage in exercises involving adapting to the environment and different tasks is believed to be critical. During such clinical gait and load

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exercises, guidance concerning the direction of movement, load position, and timing of movement at the center of gravity are often provided through auditory means such as oral instruction and visual means use of gestures, mirrors, or both. However, these instructional methods are often challenging because they can be difficult for the participant to understand.

To solve these problems, results of several studies using insoles with protrusions attached uniformly to stimulate somatosensory sensation as a perceptual measure have been reported. These studies also found that the degree of symmetry of walking or turning motions can change when the insole is inserted to only one foot⁵⁻⁷⁾ and that postural stability improves as a result of inserting insoles for both feet to activate the perception of somatosensory information⁸⁾.

Meanwhile, the Perceptual Stimulus Insole (PSI), developed by Hasegawa et al.⁹⁾, can provide sensory input to the plantar region by placing a single or multiple protrusions at the arbitrary positions on the insole. Regarding the effects of using the PSI, it was placed on the posterior side of the heel to guide the load position during initial contact (IC), and compared to free walking on bare feet, the angle of ankle joint dorsiflexion during IC, stride length, and toe height have each been reported to increase, allowing for guidance of load position and movement direction based on the sensation of plantar pressure. Thus, by directing the body weight to a specific part of the sole using the PSI, the participant actively distinguishes the plantar sensation, creating a need for fine movement control, and the PSI exhibits elements that differ from insoles containing protrusions mounted uniformly.

Unlike the PSI, this study focuses on the Perceptual Stimulus Protrusion (PSP), which directly attaches the protrusion seals to the sole of the feet, and in our previous research, we compared the respective activities of the lower leg muscles during the swing phase of gait with protrusions affixed to three different points necessary in guiding the IC position during movement (posterior, external, and internal sides of the heel). This study also reported that changes in the muscular activity occurs as a result of differences in the position of protrusions¹⁰⁾. In addition, the result of the two-dimensional motion analysis in the running motions confirmed that they are affected by the alignment of the lower limb during the standing phase¹¹⁾. However, our verifications on the effects of protrusion attachment sites other than the heels on gait and on muscle activity during the stance phase remained inadequate.

In this study, we investigated the influence of plantar sensory input and task guidance via PSP on regions other than the heels using surface electromyography and sagittal two-dimensional motion analysis with respect in order to verify the efficacy and further investigate the significance of this new approach on gait and load exercises using plantar sensory input and task guidance.

PARTICIPANTS AND METHODS

To verify using the muscle activity results, 40 healthy adults with no neurologic or orthopedic history in the lower limbs (22 males, 18 females, average age: 21.3 ± 1.0 years, average height: 165.8 ± 6.7 cm, average body weight: 59.1 ± 5.7 kg) were selected. To verify using the two-dimensional motion analysis, 42 healthy adults, based on similar exclusion criteria (25 males, 17 females, average age: 24.3 ± 3.7 years, average height: 164.8 ± 8.1 cm, average body weight: 56.4 ± 6.1 kg), were selected.

This study was conducted after obtaining in advance the informed written consent from all participants, and all research procedures used in connection with this study were implemented in accordance with the Declaration of Helsinki. This study was approved by the Ethics Committee of the Saga University Graduate School of Medical Science (No. 29-4).

In setting up the PSP, a plastic hemispherical protrusion seal (diameter: 5 mm, height: 3 mm) was directly attached to participants' soles as described in the previous study by Hasegawa et al.¹¹⁾. The affixation position of the seal for PSP is divided into two positions: the posterior lateral region of the heel, which promotes the perception of plantar contact at the time of IC, and the hallucal area, which promotes perception of the kicking-out position from the pre-swing phase of the gait (pre-swing (PSw)) to the terminal phase of gait (terminal stance (TSt)). The position of the protrusion seal in the posterolateral side of the heel was set at the position of 9% forward and 4.5% outside the foot length from the most protruding part (heel point) on the dorsal calcaneal side, as with the previous study⁵⁾. The affixation position was established when the protrusion could be perceived without pain as participants walked several meters. The hallucal area of the first metatarsal bone was used as a reference, and the area in which the protrusion could be perceived without pain during static standing and gait was set as the affixation position.

Testing conditions were as follows: participants were instructed to "please walk as usual" without any protrusion attached ("Control" condition), a condition in which the protrusion seal was attached to the posterolateral side of the heel with participants instructed to "please walk as if you are stepping on the protrusion when your heel touches the floor" (the "Heel Condition"), and a condition in which the protrusion seal was attached to the hallucal area of the sole to promote the kicking-out motion from TSt to PSw with participants instructed "during the kicking-out motion of your stride, please walk such that your body weight is placed on the protrusion seal" (the "Hallucal Condition").

For the measurement task, participants walked a distance of 10 m at a self-selected comfortable speed for each condition. The order of application of the three testing conditions was random. Before applying each condition, measurements were taken after walking for a certain period of time and after attaching the protrusion seal, confirming that protrusion could be perceived reliably without pain.

For the measurement of muscle activity, a surface electromyography km-818 MT (Mediarea support, Okayama, Japan)

Table 1. Integrated myoelectric peak relative value for each muscle during the stance phase of gait (%MVC-stance)

	Control	Heel condition	Hallucal condition
RF	18.6 ± 4.4	17.6 ± 3.8	17.9 ± 4.2
VM	18.8 ± 4.5	21.5 ± 5.8* [§]	19.7 ± 5.5
TA	15.2 ± 4.6	18.2 ± 8.5*	17.0 ± 6.5*
GM	12.1 ± 7.4	12.8 ± 8.1	18.2 ± 9.8* [†]

*p<0.05 (vs. Control condition), †p<0.05 (vs. Heel condition), §p<0.05 (vs. Hallucal condition)

Control condition: Without any protrusion attached to the heel.

Heel condition: The protrusion seal was attached to the posterolateral side of the heel.

Hallucal Condition: The protrusion seal was attached to the hallucal area of the sole.

RF: Rectus Femoris; VM: Vastus Medialis; TA: Tibialis Anterior; GM: Medial head of the Gastrocnemius.

Table 2. Integrated myoelectric peak relative value for each muscle during the swing phase of gait (%MVC-swing)

	Control	Heel condition	Hallucal condition
RF	21.8 ± 5.1	20.6 ± 3.7	20.4 ± 4.4
VM	19.0 ± 5.7	22.9 ± 5.9*	19.4 ± 5.6
TA	17.9 ± 4.8	25.5 ± 5.1* [§]	20.6 ± 5.7*
GM	23.7 ± 3.8	23.7 ± 7.8	22.8 ± 5.1

*p<0.05 (vs. Control condition), †p<0.05 (vs. Heel condition), §p<0.05 (vs. Hallucal condition).

Control condition: Without any protrusion attached to the heel.

Heel condition: The protrusion seal was attached to the posterolateral side of the heel.

Hallucal condition: The protrusion seal was attached to the hallucal area of the sole.

RF: Rectus Femoris; VM: Vastus Medialis; TA: Tibialis Anterior; GM: Medial head of the Gastrocnemius.

was used, and the sampling frequency was set to 1,000 Hz. Four muscles were measured: the rectus femoris (RF), vastus medialis (VM), tibialis anterior (TA), and medial head of the gastrocnemius (GM). Skin treatment was performed before measurement, and Blue Sensor M-00-S (Ambu, Copenhagen, Denmark) surface electrodes were attached to each muscle region at approximately 2 cm intervals in accordance with the method recommended by the Surface Electromyography for the Noninvasive Assessment of Muscles (SENIAM)¹². In addition, FlexiForce A201-25 (Tekscan, Boston, United States of America) plantar pressure sensors were attached to the heel and hallux, respectively, and gait cycles were distinguished. The right lower limbs of all participants were measured, and the electrodes were attached by the same physical therapist.

In the muscle activity analysis, values obtained by calculating the respective integrated electromyogram values (MVC) during the swing and standing phase of gait during the fourth step after obtaining the data during the third step were normalized in the swing phase after the third step and standing period of the fourth step under the Control condition (MVC-swing, MVC-stance), respectively. Then, the EMG integrated peak relative values (%MVC-swing, %MVC-stance) were obtained and compared.

Meanwhile, in the two-dimensional motion analysis, a digital video camera (HDR-CX 675, SONY, Tokyo, Japan) was used to photograph moving images on the sagittal plane for each condition. Reflective markers (diameter: 14 mm) were attached to sites such as the fibula head, lateral malleolus, and lateral side of the fifth metatarsal. The distance between the participant and the camera was set to 3m, and the height of camera was set at 80 cm from the floor. Captured video was imported to a laptop computer, and still images were created using the Image J, and the angle of the ankle joint dorsiflexion during IC, the angle of ankle joint plantarflexion during PSw, and the toe height during leg swinging each were calculated. The angle of the ankle joint dorsiflexion during IC and the angle of ankle joint plantarflexion during PSw were determined based on the angle formed by the line connecting the fibula head and the lateral malleolus as well as the line connecting the lateral malleolus and the lateral side of the fifth metatarsal head. In addition, in reference to the report by Begg et al.¹³, the three peak values of the toe height observed during the swing phase of gait were extracted. The first peak is the maximum peak value after the foot apex position during PSw (P1), the second peak is the minimum peak value when the toes are nearest to the ground during mid swing phase (MSw) (P2), and the third peak was the maximum peak value just before IC (P3). These values were calculated using the length from a perpendicular line of tape affixed along the walking path to the toe in the images obtained at the peak time point.

IBM SPSS Statistics version 25 was used for statistical processing, and one-way analysis of variance and Bonferroni's multiple comparisons test were performed after confirming the normality and equal distribution with respect to each analysis item. The level of statistical significance was set to <5% (p<0.05).

RESULTS

Regarding the muscle activity, Table 1 shows the integrated peak relative value (%MVC-stance) of each muscle during the stance phase of gait, Table 2 shows the integrated peak relative value (%MVC-swing) during the swing phase of gait, and Table 3 shows the results of each extraction item assessed during the two-dimensional motion analysis.

Regarding the changes of each extraction item for each protrusion condition, for muscle activity when standing under the Heel Condition, for the VM, the Hallucal Condition and Heel Condition showed significant increases in muscle activity when compared to Control. For the TA, demonstrating a significant increase in muscle activity under the Heel Condition compared to the Control. VM muscle activity during the swing phase of gait was observed a significant increase under the Heel Condition compared to Control. TA muscle activity was observed a significant increase under the Heel Condition compared to the Control and Hallucal Condition. Each toe height peak value at P2 was observed a significant increase during the Heel Condition compared to Control. P3 was observed a significant increase under the Heel Condition compared to the Control

Table 3. Ankle joint dorsiflexion angle during initial contact (IC), ankle joint plantarflexion angle during pre-swing (PSw), and toe peak heights for each protrusion condition

	Control	Heel condition	Hallucal condition
Ankle joint dorsiflexion angle during IC (°)	0.7 ± 1.1	10.7 ± 3.1 ^{**§}	3.2 ± 1.8
Ankle joint plantarflexion angle during PSw (°)	9.1 ± 2.8	12.1 ± 3.9 [*]	19.8 ± 5.2 ^{**†}
P1 Toe peak value (mm)	79.3 ± 9.8	85.6 ± 11.2	94.6 ± 12.6 [*]
P2 Toe peak value (mm)	42.1 ± 5.6	61.2 ± 6.1 [*]	56.3 ± 5.2 [*]
P3 Toe peak value (mm)	112.6 ± 12.8	142.3 ± 15.1 ^{**§}	129.1 ± 13.5 [*]

*p<0.05 (vs. Control condition), **p<0.01 (vs. Control condition), †p<0.05 (vs. Heel condition), §p<0.05 (vs. Hallucal condition).

P1: The maximum peak value after the foot apex position during PSw.

P2: The minimum peak value when the toes are nearest to the ground during mid swing phase.

P3: The maximum peak value just before IC.

and the Hallucal Condition. Further, the ankle dorsiflexion angle during IC was significantly higher under the Heel Condition compared with Control and the Hallucal Condition. The ankle joint flexion angle during PSw was significantly higher under the Heel Condition compared to Control.

Meanwhile, regarding the standing-phase muscle activity under the Hallucal Condition, muscle activity by the TA, indicating a significant increase in muscle activity under the Hallucal Condition compared to Control. Moreover, muscle activity by the GM was significantly higher under the Hallucal Condition compared with the Heel Condition and Control. Regarding the muscle activity during the swing phase of gait under the Hallucal Condition, muscle activity by the TA, indicating a significant higher muscle activity under the Hallucal Condition compared to Control. Regarding each toe height all peak values were significantly higher under the Hallucal Condition compared to Control. The ankle joint plantarflexion angle at PSw was significantly higher under the Hallucal Condition compared with the Control and Heel Condition.

DISCUSSION

In this study, in order to investigate the influence of plantar sensory input by PSP and task guidance on the lower limb joint dynamics during gait, PSPs were attached to the posterolateral heel side and hallucal area (Heel and Hallucal Conditions), and the effects of differences in load position were verified based on the lower limb muscle activity and two-dimensional motion analysis.

Regarding the influence of the Heel Condition on the stance phase of gait, increases in TA and VM muscle activity, increase in the ankle joint dorsiflexion angle during IC, and an increase in the ankle joint plantarflexion angle during the pre-swing phase were observed. The lower limb control for the Heel Condition in the aforementioned swing phase increases the angle of the ankle joint dorsiflexion during IC and further increases the centrifugal force exerted by the TA by increasing the range of motion of the ankle joint plantarflexion until the Loading Response (LR), and as a result of the TA's need for eccentric contraction, the TA muscle activity during the stance phase of gait increased. As a role of ankle joint dorsiflexion during the IC, Perry et al.¹⁴⁾ have referred that this joint has the stability to support body weight, transfer loads, and absorb shocks, allowing for smooth transition from the swing phase to the stance phase. In addition, when the Heel Condition works to promote ankle joint dorsiflexion during IC, it can be expected to be used in exercises to encourage smooth gait. VM muscle activity during the stance phase acts from IC to LR and absorbs impacts to support body weight when in contact with the ground¹⁴⁾. As previously described, by controlling the direction of knee joint extension by applying the Heel Condition, we believe that significant increases in VM muscle activity were observed.

As changes in the swing phase under the Heel Condition, increase in TA and VM muscle activity and increases in P2 and P3 toe height were observed. In order for the participants to step on the protrusion accurately under the Heel Condition, the heel must protrude further in the direction of movement, and as a result of controlling the foot in the direction of ankle joint dorsiflexion under the Heel Condition, we believe that increased TA muscle activity was observed. In addition, as significant increases in P2 and P3 toe height were observed, the control of the direction of ankle joint dorsiflexion was apparently achieved from the swing phase preceding the task instruction in the Heel Condition. P2 was the minimum peak value for the position closest to the ground during the midpoint of the swinging phase, and similarly to the indicators referred to by terms such as Minimum Foot Clearance (MFC)¹⁵⁾ or Minimum Toe Clearance (MTC)¹⁶⁻¹⁸⁾, it is primarily a factor related to falling and has garnered particular focus with respect to assessing ease of stumbling¹⁹⁾. Therefore, if encouraging increases of the toe height is possible through the method evaluated in this study, it can be possibly applied as a tool for gait exercise intended to prevent stumbling and falling. In addition, the VM is believed to be active during the terminal swing (TSw) component during normal gait¹⁴⁾. As also described previously, control over the angle of the ankle joint dorsiflexion that directs the movement of the heel is required under the Heel Condition, and as such the knee joint needs to be controlled in the direction of the extension accordingly. Thus, under the Heel Condition, by guiding the direction of knee joint extension, we believe that VM muscle activity will increase in order to properly ground the protrusion from TSw to IC.

Regarding the changes during the stance phase under the Hallucal Condition, increased TA and GM muscle activity and increased ankle joint plantarflexion angle during the pre-swing phase were observed. To successfully perform the task instructions, anterior movement of the center of foot pressure (COP) accompanied by ankle joint plantarflexion and toe to MP joint extension are required. Further, to successfully balance load under the Hallucal Condition, moving the body's center of gravity (COG) forward should be controlled. Stated differently, to balance load under the Hallucal Condition, we believe that an increase in the ankle joint plantarflexion angle occurred as a result of the anterior movement of the COP and an increase in GM muscle activity due to anterior movement of the COG.

As changes in the swing phase in the Hallucal Condition, increased TA muscle activity and increased toe height peak value were observed. Under the Hallucal Condition, increased toe height and increased TA muscle activity were observed in the swinging leg in order to strengthen the kicking out motion during PSw and complement foot clearance at angle of ankle joint plantarflexion during the forward swing phase to be described later.

Based on the above results, changes in the muscle activity were observed in specific muscles during both stance and swing phases of gait, and a two-dimensional motion analysis revealed the effects of these changes on the foot dynamics during gait. Therefore, these results suggested that PSP and task guidance prompted active control of gait movements by participants. PSP promotes the perception of stimuli impinging on a specific part of the sole, and in response, we believe that participants begin to actively judge how to control the movements of the lower limbs during PSw as needed to satisfy the respective conditions.

Meanwhile, regarding the task guidance during the stance phase of gait the area to be loaded should be controlled based on the differences in PSP position. In other words, the task of "placing weight on the protrusion position" via PSP should be carefully considered in order to determine the sensory changes under the sole of the foot, such that participants seek the ability to consciously and subjectively control the spatial position of the lower limbs. Essentially, movements should be performed while activating both aspects of the musculoskeletal functions related to motor control and nervous system functions related to conscious perception of the sole, and participants must engage in situational adaptation as a means of improving foot and lower limb alignment. We believe that this method can be expected to be used as a novel tool for mobility support that can be applied to the internal aspects related to gait, including methods of targeted training that focused on the muscles and cognitive processes. For example, under the Heel Condition, the result on the TA and VM accompanying the degree of control in the ankle joint dorsiflexion necessary from the swing phase to LR, and under the Hallucal Condition, the effects on the toe MP joint extension were necessary to move from TSt to PSw, and on ankle joint plantarflexion control accompanying the effect on GM can be considered. With regard to future developments, the reports published to date discussing plantar sensation mention finding that elderly participants perceived sponges of several different degrees of firmness touching their soles, and by distinguishing the firmness of these sponges, the degree of fluctuation in participants' COP while standing and performance on the Functional Reach Test significantly improved²⁰), that plantar perception ability contributes to gait stability²¹), and that the capacity to perceive stimuli impinging on the plantar region is important to control posture. As such, if plantar perceptive ability can be incorporated with PSP, this technique may be used as a novel method for enhancing postural control.

One limitation of this study is that because the influence of plantar sensory input was examined via the PSP and task guidance, the extent of respective impacts of PSP and task guidance was not determined. Therefore, PSP and task guidance should be performed separately in future studies, and more detailed evaluations on the influence of other factors affecting gait should be conducted.

The above observations suggest that PSP may be effective as a novel approach to mobility guidance utilizing somatosensory perception as selective training targeting specific muscles involved in the lower limb joint dynamics during gait. PSP also offers clinical versatility by involving the attaching protrusion seals to the sole of the feet, and replacing the protrusions with other similar types is also possible. Thus, this method is easy to apply on gait and load exercises in the clinical environment and is expected to serve as a supporting tool for mobility guidance.

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Conflicts of interest

None.

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