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Sensory perception of unexpected sudden changes in floor level during human gait

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***Abstract*— Possible clues for sensory perception of an unexpected sudden change in floor level during human gait could be discrepancies in the time of heel contact, location of force application point (center of pressure, CoP) in the sole at the heel contact and subsequent stance period from the ones prescribed prior to the gait execution prepared for the normal level gait, if they exist. In order to get insight for this perception mechanism, a psychophysical experiment during gait on a walk way with a small, unexpected and sudden change in the floor level was performed, in which the subject was forced to answer among step-down, flat, and step-up immediately after the walk. During the gait, foot pressure distribution (FPD), electromyogram (EMG) of the ankle muscles, and gait trajectory (GT) were measured. The experiment could quantify accuracy of the perception. The floor level change dependent changes in FPD, CoP trajectory, EMG, GT were examined to suggest that these changes might be the clues for the perception.**

I. Introduction

Desired gait trajectory during normal level walk may include the time of each foot contact, location of force application point (center of pressure, CoP) in the sole during the stance phase, and joint angles, if it exists and prescribed prior to the gait execution with a certain precision. Hence an unexpected sudden change in floor level during human gait causes discrepancies in those for the realized gait. Possible clues for sensory perception of the unexpected sudden change in the floor level during human gait could be those discrepancies, based on which the human central nervous system (CNS) could modify the gait trajectory to avoid fall. If there is a threshold for the perception, CNS may not be able to perform the modification for a floor level change which is below the threshold, and the walker will keep the prescribed gait trajectory as if there were no change in the floor level. If the threshold were pathologically high, the walker would not be able to adjust the gait trajectory and fall down. The threshold value, if exists, could be closely related to the existence of desired gait trajectory and its precision. In this study, we performed a psychophysical gait experiment described above to quantify such a level step size associated to the perception threshold. In the experiment, foot pressure distribution including CoP, the time of heel contact, gait trajectory, and electromyograms (EMGs) of the ankle muscles were measured to see if changes in these could be the clues for the perception.

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II. Materials and methods

A. Experimental Protocol

19 healthy subjects (21-38 years old) participated to the experiment. The informed consent was obtained from all subjects. Hard rubber boards of 1 m square with 5 mm thickness were used as sheet-mats to prepare the walking way. They were aligned at adjacent two sites to make the walk way with 2 m length (Fig. 1) on which the subject walked. A difference in the floor level, referred to as a step-level, was determined by the number of piled up boards for each site. Eight step-level sizes, every 5mm from 20 mm down to 15 mm up, were examined. 20, 15, 10, and 5 mm down-steps were referred to as -20, -15, -10, -5 step-level sizes, and they were with plus signs for up-step sizes. A step-level size for each gait trial was not informed to the subject, and the subject walked with wearing a sunglasses, lower half of which was covered to shut the floor view out so that the subject must judge the step-level only by somatic sensation of the foot. The subject was in normal upright posture and started a walk from the 1st step of right leg under the instruction of the experimenter. The second step by the

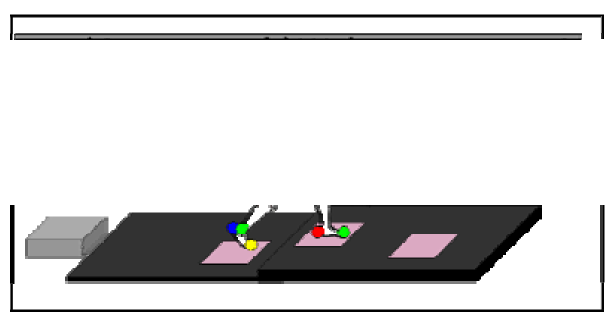

Fig. 1. Experimental setup. EMG surface electrodes, color markers for motion capturing, and in sole foot pressure sensors were attached to the subject. Piezoelectric sheet device was installed under the rubber to detect every foot contact.

left leg crossed over the level-step and its foot contact was made on a different floor level, and then stopped with 3 and 4 steps putting together. Single set of experiment consisted of 36 walk trials by changing the step-level randomly. Each of eight step-levels was examined 4 times, except 0 mm (flat) which was examined 8 times. Immediate after the 4th step, the subject was forced to choose an answer among "*step-down*," "*flat*," and "*step-up*." One of the following four experimental conditions were employed:

1. The subject performed 36 walk trials in succession without wearing any measurement sensors.
2. The subject performed 36 walk trials as in 1. Between each trial, however, the subject forced to walk freely on a normal ground of about 30m. With this condition, a possible influence of after-effect of the preceding trial on the perception was examined [1], [2].
3. The same as condition 1, plus foot pressure distribution and gait trajectory were measured by insole sensors and a motion capture cameras to measure the step-level dependent changes in CoP trajectory.
4. The same as condition 1, plus EMGs and gait trajectory were measured to look at the step-level dependent changes in EMGs of ankle muscles.

B. Data recording

The foot pressure distribution was obtained using a pressure sensor sheets (F-SCAN, Texscan, USA), in which the subjects wore a rubber foot shoe on each foot with the sensor as insole with the sampling frequency 169 Hz. Electromyograms (EMGs) were recorded by surface electrodes using a differential amplifier (bandwidth 10 Hz to 200 Hz). The electrodes were placed over muscles of the right tibialis anterior (TA) and soleus (SO) with an interelectrode distance of 20 mm. A 12-bit A/D converter with 1-kHz sampling frequency was used. Measured EMGs were numerically rectified. The gait trajectory was measured using 15 color markers attached at chest, hips, knees, ankles, and feet by 6 CCD cameras (OKK, QuickMAG-IV, Tokyo). The sampling frequency was set to 60 Hz. When the foot pressure distribution was not measured, the times of heel contacts were detected using Piezo-sensor sheets (Tokyo Sensor, NiCu alloy, Tokyo) placed under the rubber sheets with the sampling frequency 1000 Hz. The samplings of all sensors were not synchronized, but the start of the samplings was triggered simultaneously.

III. Result

A. Accuracy of sensory perception changed as step- level

For each step-level, the number of correct answers for all subjects was divided by the total number of trials with that step-level to calculate the rate of correct answers, and it was plotted as the function of the step-level size (Fig. 2). The rates of correct answers in its average were higher than 0.8 for all up-step-level sizes and for -15 and -20 step-level sizes, implying that those large step-level sizes could easily be perceived with high accuracy. In particular, all subjects could perceive +15 step-level for all trials. The lowest rate was reached at -5 step-level, at which the rate of correct answers was below 0.3 in its average. Note that no significant differences in the rate curves were found among 4 different experimental conditions.

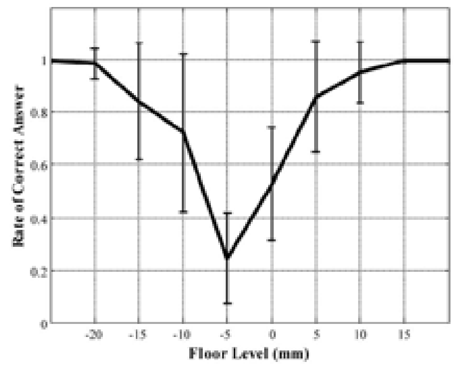

Fig. 2. The rate of correct answers for all subjects as the function of step-level size. 20, 15, 10, and 5 mm down-steps were referred to as -20, -15, -10, -5 step-level sizes, and they were with plus signs for up-step sizes. The error bars represent ±1SD.

B. Foot pressure distribution and CoP motions

Fig. 3 exemplifies the snapshots of the foot pressure distribution at 300 msec after the left heel contact of 2nd step. The upper four foot prints were for -20, -10, 0, and +10 mm step-level sizes, in which the subject perceived the step size correctly. The lower left and right were, respectively, for -15 mm with the answer as "*flat*" and for -5 mm with the answer as "*flat*". The six curves in Fig. 4 are the forward CoP movements from the heel contact site corresponding to six foot prints in Fig. 3. These figures showed that the CoP

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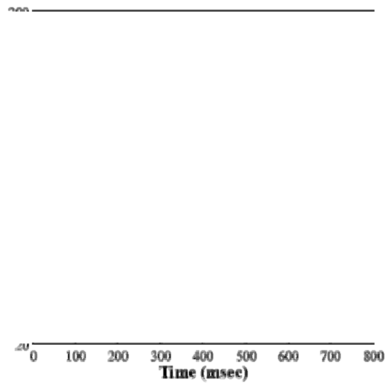

Fig. 4. Forward motion of CoP of the left foot after the heel contact of the 2nd step for four different step-levels. The vertical axis is the distance from the most rear edge of the insole sensor close to the heel toward the toe. Black dashed line: -20 mm. Black dotted: -10 mm. Black solid: 0 mm. Black dot-dashed: +10 mm with the correct answers for those. Gray dashed: -15 mm with the answer as "flat". Gray solid: -5mm with the answer as "flat".

moved forward slowly for the up-step. Faster the moving velocity, larger the size of down-step-level was. In other words, the CoP stayed around the heel for a long period for the up-step-level walking. The CoP position at 300 ms after the heel contact for -15 and -5 mm shown in lower row of Fig. 3 were close to the one for the flat (0 mm), and the answer of the subject to those down-step were the flat. These situation could also be confirmed by the CoP motions for the initial time interval of Fig. 4 (200-300 msec) in which the gray curves changed closely along the black solid curve corresponding to the gait on 0 mm step-level (flat) walk way. This means that the wrong perceptions of the subject matched with the CoP motion.

C. Step-level dependency of EMGs

Rectified EMGs of TA and SO from the left leg were exemplified in Fig. 5, in which the heel contact time of the 2nd step of the left leg was taken as the origin of the time axis for every trace. Subject answered correctly in all traces, except the 5th trace from the top marked by the thick box, in which -5 mm step-level was incorrectly perceived as flat. The first observation was that the maximum activation of TA appeared after the heel contact for up-steps, and before the heel contact for down-steps. Amplitude of the maximum was the smallest for the flat walk, and tended to be higher for the up-steps. These were consistent with the results obtained in the foot pressure distribution, in which the CoP stayed around the heel for longer period after the heel contact, implying that the ankle flexor activity was required to move the body forward against the load caused by the up-steps.

The SO activity after the heel contact was higher for the down-steps and sustained during the stance phase, whereas it was inhibited for hundreds millisecond in the case of up-step walking. The heel contact was made during TA activity for the up-step cases, and the TA activity was enhanced somehow by the heel contact. The enhanced TA activity could reduce the SO activity due to the reciprocal

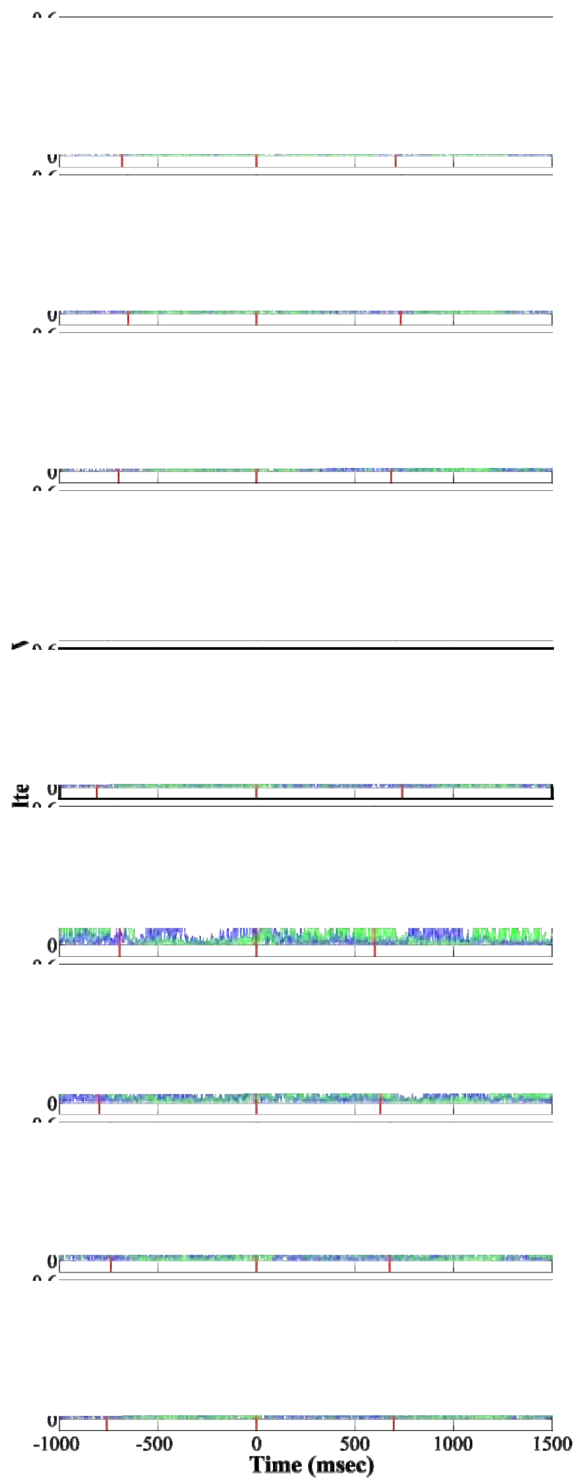

Fig. 5. Rectified EMGs of TA (blue) and SO (green) for the left leg. The origin of the time axis for every trace was set to the heel contact time of the 2nd step of the left leg. Subject answered correctly in all traces, except the 5th trace from the top marked by the thick box, in which -5 mm step-level was perceived as flat.

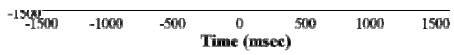

Fig. 6. Vertical motion velocity of the marker attached at the left heel around the time of the heel contact of the 2nd step of the left foot. The origin of the time axis for every trace was set to the heel contact time of the 2nd step of the left leg. Blue curve: -20 mm. Cyan: -15 mm. Green: -10 mm. Orange: +10 mm. Red: +15 mm. All trials were with the correct answer.

inhibition between the antagonistic muscles. This could also account for the low and delayed activity of the SO muscle.

As in the case of the foot pressure distribution, the trace of EMGs of TA and SO for the -5 mm down-step with the incorrect answer as “flat” was similar to the EMG trace for the flat walking, implying again that the EMG activity matched with the perception of the subject, regardless the correctness of the subject’s answer.

D. The timing and heel velocity at the heel contact

Fig. 6 shows the vertical motion velocity of the marker attached at the left heel around the time of the heel contact of the 2nd step of the left foot for the walking with 5 different step-levels. As in Fig. 5, the origin of the time axis for every trace was set to the heel contact time of the 2nd step of the left leg. Fig. 6 illustrates that the left foot in the swing phase reached the maximum velocity at the first positive peaks around -500 ms, and then made slowdown to reach the highest position in the middle swing at the zero-crosses of the curves. The foot started to fall toward the ground rapidly, but made slowdown again about 100-400 msec before the heel contact, and the falling velocity became close to zero. The CNS producing the gait cycle [3] might be anticipatory ready for the foot contact at the instant, and the falling velocity increased again. Within this accelerating interval, the foot contact was made, leading to the heel contact with relatively slow impact velocity for early heel contact, and fast impact velocity for late heel contact. Since the curve aligned by the heel contact time-shifted leftward systematically as the step-level size changed from positive to negative, and it implies that the heel contact timing in the normal gait cycle was early for the up-steps and late for the down-steps, the impact velocity at the heel contact was fast for the down-steps, and it was slow for the up-steps. This observation was also consistent with the CoP motion velocity, and thus with the EMG activity.

The difference in abovementioned peak timings (indicated by three arrows in Fig. 6) between -20 and +15 mm step-levels could be estimated as about 300 msec, implying that the time difference produced by 5 mm difference of the step-level size was about 40 msec. This small time difference may or may not be perceived by the CNS somehow by making use of the anticipatory generation of its neural activity during the gait cycle.

IV. Discussion

Our experimental procedure allowed the subject to get correct answer 33% by chance. The lowest rate of correct answers for -5 mm step-level was lower than this probability, suggesting that the sensory perception threshold for the step-level was close to -5 mm, but not +5 mm. In other words, the neural responses of either peripheral motor sensations and/or the CNS to the heel contact and the subsequent gait kinematics was similar, and they were not sensitively separated between -5 mm and 0 mm step-level walking.

The possible clues for sensory perception of an unexpected sudden change in floor level during human gait could be listed as follows: 1) CoP motions, in particular velocity of forward motion during which the stance foot touched down on different floor level experienced the heel contact and then foot flat. 2) Different EMG time course of the ankle muscles. This difference could be induced either by the mechanical factors due to the difference in the CoP motion or the neural factors due to, for example, the reciprocal inhibition between the antagonistic muscles.

It was shown that the accuracy of perception for the up-step was higher than that for the down-step when the absolute value of the step-level size was the same. Possible reason for the underlying mechanisms that account for this result could also be either mechanical or neural. The results associated with the heel contact events (the impact velocity, and CoP motions) seem to be mechanical factors that generate different neural responses as the result. However, the perception of the heel contact timing, which was shown to be about 50 msec or less, by comparing the actual timing and the prescribed one, could be the CNS-related mechanism.

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