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Passive arm swing motion for virtual walking sensation

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Abstract

The present paper describes the characteristics of an arm swing display as a part of the multisensory display for creation of walking sensation to the user who is sitting on a vestibular display (a motion chair). The passive arm swing by the display was evaluated regarding the sensation of walking. About 20 % smaller (from 25 to 35 degree) passive swing angle than a real walking motion could effectively enhanced the sensation of walking when displayed as a single modality stimulus for a walking of 1.4 s period. The flexion/extension ratio was shifted forward from the real walk. The optimal swing obtained by the method of adjustment showed the same characteristics. The sensation of walking was markedly increased when both of the passive arm swing and the vestibular stimulus were synchronously presented. The active arm swing raised less walking sensation than the passive arm swing, which might be ascribed to original passiveness of the arm swing during real walking.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1. Introduction

The walking sensation activated in a virtual space enhances presence of the space [SUS95], which could contribute to the effectiveness of the virtual reality experience. The sensation of walking is crucial also in the application of a virtual reliving experience of others that plays back their spatial activity. In the reliving application, all the stimuli are passively given to the user from both the virtual environment and the virtual body that walked in the past. Walking is a whole body motion where the body is actively moved and the multisensory sensation is fed back in the sensory-motor loop to be used to control the motion consciously as well as unconsciously. Thus, the conscious part of walking sensation is closely related to the unconscious part, which makes a challenge in the virtual presentation of walking sensation where many aspects should be addressed.

One approach to virtually simulate the walking is to use the real walking body (including deformed walking motion) of the participant as a part of the VR experience [IYN01, Hol02, SUS95, PFW12], and the other replaces the part of information in the loop by that from devices without doing the walking motion to evoke the sensation [JMDO12, TBS13, TS14, TMM*12]. These studies mostly focus on the feet as direct media to enhance the reality of walking. However, the motion sensation of the upper arms is important as well as the lower limbs, since we know that we feel frustrated if the arms were bound to the body to prohibit the motion during walking. The lower limbs motion for walking presentation has been discussed for its contribution [IOS*14]. The upper limb motion display has not been developed in this virtual presentation context except for the motion display used in the rehabilitation [JNC*10]. The sensation of virtual walking could be augmented by introducing the arm swing as observed in the natural walking.

Although the natural arm swing in the human walking is very common motion, its mechanism is not fully elucidated [MBD13]. The arm swing during walking is considered to improve efficiency of motion [Umb08] by regulating the moment of force due to the motion of the lower limbs and the trunk. It also has the stabilizing function [BMB*10] to balance the body during gait motion. The arm motion is almost automatically (without intention) introduced as a part of a walking motion. The arm swing is thought partly to be driven passively by the body motion [GJDB14], however, at the same time, its muscle activity regulates the phase of the motion and increases the amplitude of the swing. In both aspects, the arm mo-

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tion is usually not controlled by the conscious attention, or active will. The cyclic motion of legs is controlled by the CPG (central pattern generator) in the spinal cord [DGP98, DdCH98]. Although the arm swing may also be regulated by the CPG [WBCD01] through the interconnected neural system, direct evidence has not been shown. Indirect arguments to support the coordination between arms and legs include the frequency selectivity in oscillation, the interlimb neural connections and reflexes, and other behavioral interrelation between the arm swing and the leg motion [MBD13].

The objective of the present study is to develop an arm swing display that rotates upper arms around the shoulder to simulate the arm motion during the real walking. With the display device, we investigate a method to impart the sensation of walking to the user sitting on the motion chair as a base for the reliving system that transfers other's bodily activity to the user.

2. Arm Swing Display

Figure 1 shows the arm swing display that moves the upper limbs of the user alternately and similarly to the arm swing that occurs in the real walking. The end of the swing link of the display is fixed to the upper arm of the user by a velcro strap. The pillar of the arm swing display is attached to a vestibular display (a motion chair). The motion of the swing arm is driven synchronously with other displays (the vestibular display, feet motion displays, foot-sole tactile displays) in common usage. The upper arm holder rotates around the axis that is placed approximately to the position of the shoulder joint. The range of rotation is 230 deg to the front and 50 deg to the backward of the user. The rotation speed is up to 120 r/min with the torque of 8 Nm (max). The vestibular display [ISK*14] has three linear actuators that drive the chair with the lifting, rolling and pitching motion. This three dof (degrees of freedom) motion produces the stimulus that imparts the sensation of walking to the sitting user. The optimal amount of the lifting was less than 2 mm, and the rolling/pitching less than 0.2 degree. These are five to ten percent of the motion in a real level walking.

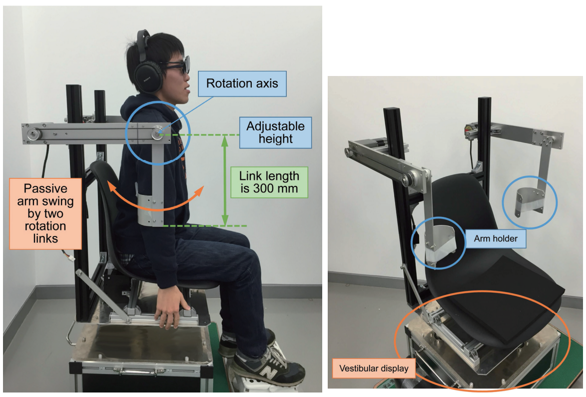

Figure 1: *Arm swing display mounted on a vestibular display (a 3-dof motion chair).*

2.1. Arm-swing shoulder angle during real (natural) walking motion

To obtain the characteristics of arm swing during a real walk, the position of the arm was measured by an optical motion capture system (OptiTrack Trio, NaturalPoint, Inc.). Figure 2 shows a typical trajectory of a shoulder joint angle when the participant walked on a treadmill at a walk period of 1400 ms. The mean angle of the shoulder joint of twelve participants (22 years old, 1714±74.4 mm tall in the mean±SD) was 37.8 deg with a SD of 9.73 deg. The forward rotation angle ratio from the vertical direction was 38.3±3.7 % (mean and SE. About 62 % of rotation angle was backward relative to the trunk).

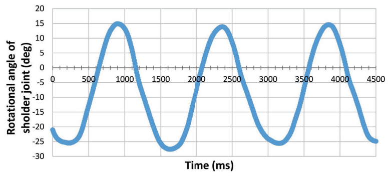

Figure 2: *A typical shoulder-angle trajectory of the arm swing during a real walk (on a treadmill).*

2.2. Rotation-angle trajectory of the arm swing display

Figure 3 shows the rotation trajectory of both links of the arm swing display. In this example, the amplitude was 35 degrees, and forward/backward ratio 3:2 (67 % forward 33 % backward). This shape of the trajectory was designed to simulate the real shoulder rotation trajectory (Fig. 2). The first start segment of the trajectory is a transient part. The next segment has a shape that was repeated both in forward and backward motions. The shape of the waveform consists of a constant acceleration segment for the first 2/7 period, then a 3/7 period of a constant velocity, and the last 2/7 period of constant deceleration in a min-to-max (max-to-min) rotation.

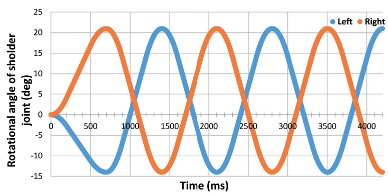

Figure 3: *Link angle trajectory to present the arm swing in a VR walk. An example waveform of amplitude 35 deg, forward/backward ratio 3:2.*

3. Preliminary evaluation of passive arm swing stimulation

3.1. Objective

The passive arm swing was preliminarily investigated by adding several waveforms of arm motion to the participant who sat on a stationary chair. The amplitude and the rotation-angle ratio were changed to find the optimal stimulus that best created the sensation of a walk. Two separate sessions were performed to decrease the time for each session.

3.2. Participant

In the first session, seven graduate/undergraduate students, the mean age of 23.3 years, volunteered the experiment. The participants of the second session were 10 students of 22.7 years old in the mean. All of them were the lab members and familiar with the sensation rating task. (The same for the rest experiments.)

3.3. Stimulus and an evaluation scale

The period of arm swing (a walk period) was 1400 ms. The amplitude set of the first session was {0, 10, 20, 30} degrees. The forward/backward amplitude ratio set was {0:10, 1:4, 2:3, 1:1, 3:2, 4:1, 10:0}(i.e. forward ratio of 0, 20, 40, 50, 60, 80, 100 %). In addition, the walking sensation by an active (voluntary) arm swing without the swing display device was rated. The amplitude of active swing was not instructed by the experimenter. The participant moved the arms to the tone of a metronome at 700 ms. For the second session, the amplitude set was {25, 35, 45, 55, 75} degrees and the forward/backward ratio set was {1:5, 1:2, 1:1, 2:1, 5:1}(i.e. forward ratio of 17, 33, 50, 67, 83 %). The stimuli were presented in a random order. The participant closed eyes and a white noise was provided via headphones. In an active swing turn, a tone of a metronome at 700 ms was presented by the headphones. No vestibular stimulation was added in this preliminary experiment.

The walking sensation evoked by each swing stimulus was rated using an analogue visual scale. The anchor of the evaluation scale was from 'no sensation' to 'equivalent to real walk' at the both ends of the line segment of the scale. The rating was mapped to 0 to 100 in the graphs of walking sensation.

3.4. Results

Figure 4 shows the results of session 1 in light gray, and session 2 in gray with all ratios pooled. The walking sensation was highest at the amplitude range from 25 to 35 degrees (30 degrees in the mean) that is about 20 % smaller than the mean swing amplitude of 37.8 degrees of a real walk, although the difference is not very large. This is an interesting result since the equivalent passive stimulus for vestibular and proprioceptive sensation was very small relative to the real motion. The amplitude of a motion chair as an input to the vestibular sensation to evoke a virtual walking sensation was around 7 percent of the head movement in a real walk [ISK*14]. The heel lift to impart the sensation of a foot motion as a gait cycle was also about 10 percent of the real lifting of the heel during actual walking [IOS*14].

The active arm swing (shown on the left end) did not produce the sensation of walking as high as the passive swing at the optimal amplitude, although the variance of rating was large. This relation seems to stem from the origin of arm swing. The swinging the arm during a real walk has two functional bases, mechanical coupling with legs and the torso, and regulatory activity of muscles. The swing of arms is passively induced by motion of legs and the torso without active muscle torque to lift the hands. The regulation of swing trajectory is performed almost unconsciously and not controlled intentionally. On the other hand, this active swing condition in the experiment was performed by conscious direct control

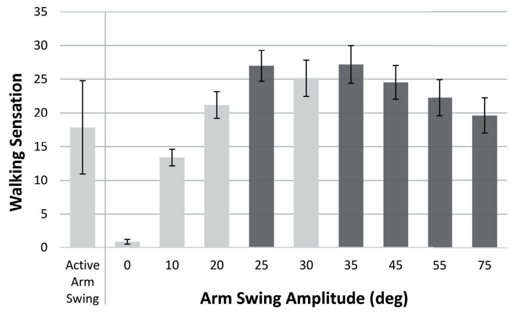

Figure 4: *Walking sensation evoked by passive arm swing. (The left end bar indicates walking sensation by active arm swing in a seated posture.)*

of arm muscles by the participant, and it is largely different from the natural swing in an ordinary walk. This contradiction may have caused the decrease of walking sensation.

Figures 5 and 6 show the dependency of walking sensation on the forward/backward swing angle ratio for sessions 1 and 2, respectively. The forward/backward-ratio mean in terms of the weight center of walking sensation of the sessions was 52.6 % (forward side) for session 1 (Fig. 5) and 53.3 % (forward side) for session

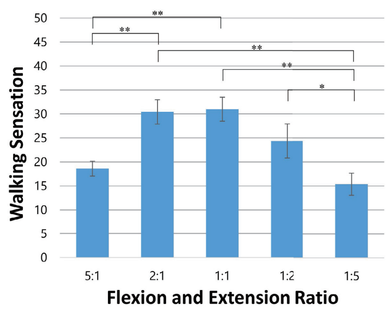

Figure 5: *Walking sensation for each flexion/extension ratio of Session 1.*

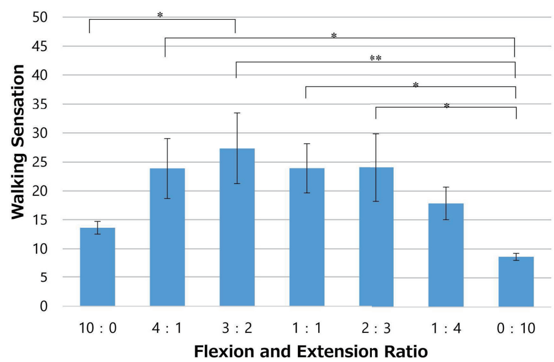

Figure 6: *Walking sensation for each flexion/extension ratio of Session 2.*

2 (Fig. 6). These figures do not have a significant difference from 50 %, however they differ significantly from the forward angle ratio of 38.3±3.7 % of a real (natural) walk shown in section 2.1. In the real walking motion, the backward angle was larger than the forward angle. The reason of this discrepancy is not known at the moment. This may arise from both the posture difference and the attention of the user on the display system. The sitting posture places the center of mass of the body behind the feet, and the attention to the forward rather than to the ground on which the body has to be stably controlled, which may induce the swing to the forward.

4. Optimization of arm swing trajectory by the method of adjustment

4.1. Objective

The optimal amplitude of passive arm swing that imparted the sensation of walking was investigated by the method of adjustment.

4.2. Participant

Eleven graduate/undergraduate students (the mean age of 22.6 years) participated in the experiment.

4.3. Procedure

First, the participant was asked to walk on the flat floor at a 1400 ms walk period about at least 20 m to memorize the sensation of upper limb motion. Then, the participant sat on the chair so that the axis of rotation of the link of the device was adjusted to the height of the shoulder joint. The link of the display was attached to the participant's upper arm, and headphones emitting white noise masked the sound of the devices. The motion of the vestibular display was set to its optimal presentation to impart the sensation of walking by only the seat motion stimulus. The participant adjusted the motion of the arm swing by oral commands to the experimenter to increase the sensation of walking. The commands were to increase/decrease the forward (flexion) amplitude, the backward (extension) amplitude, and the total amplitude with fixed forward/backward ratio. The initial amplitude was selected randomly from {10, 20, 30, 40} degrees. The initial flexion/extension ratio was 1:1 for all the amplitudes.

4.4. Result

Figure 7 shows the result of adjusted amplitude and walking sensation as a function of four initial amplitudes. There was clear hysteresis with an initial amplitude. The adjusted values differed in the changed amount of increase for {10, 20, 30} degrees and decrease for 40 degrees. The mean amplitude was 28.8 degrees with the 3:2 forward/backward ratio (59.4 % forward). Since the larger increase was observed in lower initial amplitude and the decrease was selected at the 40-degree initial amplitude, the mean value (28.8 deg) would not be a good estimate for the current experiment. The mean of two amplitudes obtained from 30 and 40-degree initials may be more probable considering the hysteresis from error of habituation. In that case, the mean is 35.0 degrees.

After the adjustment, the sensation walking was also rated. The walking sensation was about the same at 35.5 (right y-axis, 100 equals to the real walk) regardless of large difference in the amplitude that was pulled to the initial value. This hysteresis suggests that the arm swing is not necessarily perceived very consciously in its usual passive form of generation. The arm swing motion is generated automatically in accordance with the whole body walking motion. The walking sensation in this vestibular/arm swing condition was higher than the single stimulus presentation in the previous section.

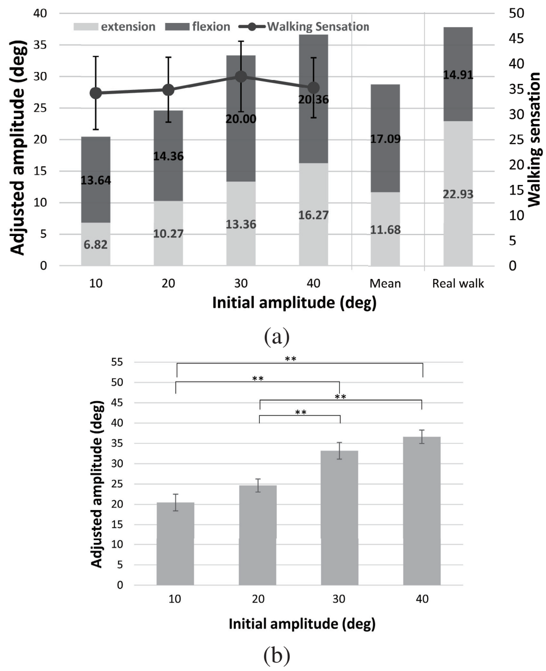

Figure 7: *Amplitude and the walking sensation after the adjustment from four initial amplitudes. (b) shows significant difference (p<.01).*

5. Walking sensation by combined presentation of arm swing and vestibular input

5.1. Objective

The walking sensation evoked by simultaneous presentation of arm swing and vestibular stimulation was evaluated. The phase delay and the active swing were also compared.

5.2. Participant

Eight graduate/undergraduate students of the mean age of 24.3 years volunteered the experiment.

5.3. Procedure

The number of the stimulus set was eight as shown in Table 1. The stimulus set was from options of w/wo vestibular stimulation by the motion chair, w/wo arm swing at the amplitude of 35 degrees, swing angle ratios (front/back) of 1:1 and 2:1, in/opposite phase vestibular/swing stimuli, and passive/active arm swings. The opposite vestibular/swing stimulation drove the arm with 180 degree delay from the vestibular motion (that equivalently indicated the foot motion). The active arm swing means that the participant moved the arms voluntarily in accordance with the vestibular motion without the swing link device (retracted). The standard stimulus was the real walk on a flat floor at a 1400 ms walk period.

The stimulus was presented to the participant with closed eyes and masking headphones, in a random order after the real walk. The participant rated the stimulus for its sensation of translation, the amplitude of swing motion, the sensation of passivity and activity, and the sensation of walking with an analogue visual scale (0:no sensation, 100:the same as a real walk). The walking sensation was analyzed by the Fisher's LSD method.

Table 1: *Stimulus combination (name).*

Arm Swing Ratio (Flexion/Extension)	No Arm Swing	1:1	2:1	1:1	2:1	Active swing
Vestibular Stimulation	A	D	E	F(+Φ)	G(+Φ)	H
No Vestibular Stimulation	-	B	C	-	-	-

5.4. Results

Figure 8 shows the walking sensation under the eight stimuli. The left three bars of single modality stimulation (A, B, C, only vestibular and only passive arm swing) produced the same low level walking sensation. Although the absolute value was lowered as compared to the preliminary evaluation (Fig. 4), the difference was not significant. The combined (in-phase) stimulus (D, E) produced markedly larger walking sensation at the 0.01% significance level. The opposite phase (F, G, out-of-phase) stimulus lowered ($p<0.1$) the walking sensation from the in-phase stimulus. The active arm swing (H, on the right end) also increased the walking sensation ($p<0.1$) from A. It might be worth pointing that the passive arm motion was better than the active arm motion for creating walking sensation.

Figure 9 shows the sensation of translational motion with the value ranging 0 for standing-still to 100 for a real walk. The highest value was achieved when both of passive arm and vestibular stimulation were presented although variance was larger than the walking sensation. The passive arm swing only did not contributed to the sensation of translation. Figure 10 shows the sensation of arm swing relative to the swing sensation in the real walk. The passive swing of 35 degrees was felt 12 % larger than the real walk swing in this presentation.

Figure 11 shows the sensation of passivity and activity. The full (100 %) passivity was the sensation in which the body was controlled by external force regardless of own will. The full activity is the sensation where the body is completely controlled by the own will. It should be noted that the real walk is not fully active nor its passivity is zero. This rating seems to stem from that the walking is not controlled completely by the conscious will, but only partially directed by own will.

The active arm swing with the vestibular stimulus (H) was rated

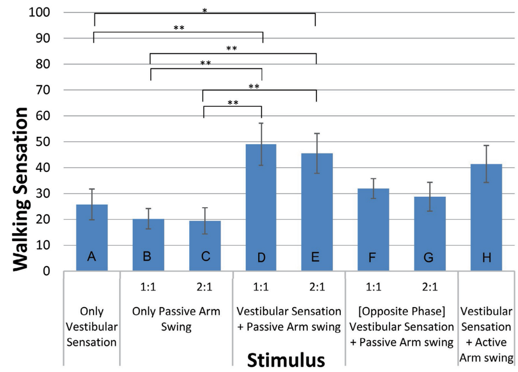

Figure 8: *Walking sensation for eight stimulus conditions.*

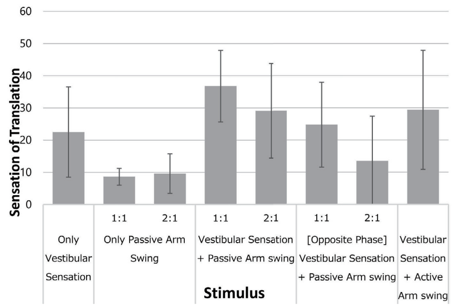

Figure 9: *Sensation of translational motion.*

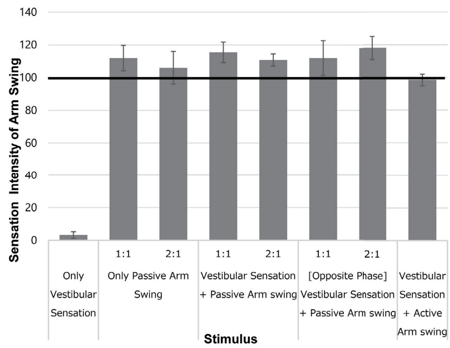

Figure 10: *Sensation intensity of arm swing.*

highly in activeness. At the same time, its passivity was more than twice as large as the passivity of the real walk. The passivity of other stimuli than H was very high as compared with the real walk, while the activity was low. The vestibular and passive arm swing (D, E) could lower the passivity and increase the activity.

5.5. Discussion

The first preliminary experiment suggested that the passive-swing arm stimulation as single proprioceptive body motion input was able to evoke the sensation of walking at considerable high ratio of about 26 % relative to the real walk. This figure may not be

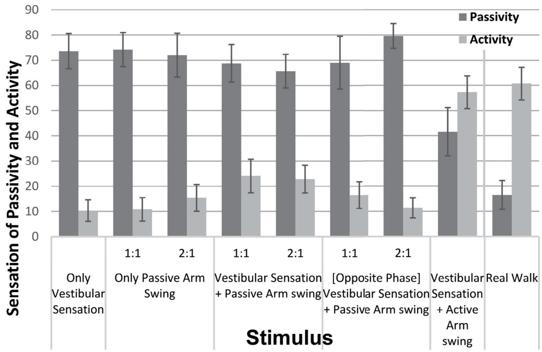

Figure 11: *Sensation of passivity and activity.*

disregarded considering that stimulation of both leg motion and body acceleration (vestibular input) were not provided. The amplitude range appropriate to invoke walking sensation was 25 to 35 degrees that is about 20 % lower than the natural swing amplitude during a real walk. This is rather a high-ratio agreement than other passive stimulation channel of vestibular and proprioception of legs. In the active body motion, the sensory reafference is usually suppressed [SF12] based on the corollary discharge indicating the prediction of the sensory input [WMK98]. The passive drive of body motion is considered not to produce the efference copy for the predictor, and also the corollary discharge. Then, the sensory input caused by the limb motion driven externally is not suppressed to make too large motion sensation. This interpretation justifies the very small motion input needed for leg proprioception and vestibular sensation to produce the virtual walking sensation [IOS*14, ISK*14]. In the case of an arm swing, the swing motion is basically not active (voluntary) motion, so the sensory input is usually not suppressed. Then, if the motion is produced by external mechanism, it is similar to the natural arm swing condition. This might be the reason of the amplitude comparable with the real walk needed for the virtual walk.

The vestibular stimulus added to the swing stimulus in Fig. 7 caused the increase of the walking sensation from the single arm swing stimulation in Fig. 4. This shows that the both stimuli contributed to the sensation of walking. The difference of swing amplitude between the real walk and the display decreased in the same line.

The vestibular and passive arm presentation (D, E) was considered effective in creation of the sensation of walking, since the sensation of walking and translation were increased from single modality stimulus (A, B, C) and the passivity was lowered. The contribution of the vestibular stimulus and the passive arm motion might be independent since the rating of D, E was near to A+B, A+C. However, its synchrony (in-phase stimulation) is important for this additivity. The synchrony allows to provide predicted motion sensation, which suggested that the motion was originated by own action.

The active arm swing (H) marked high rating of both walking and translation probably due to the voluntary arm motion used. However, it is interesting that the passive arm swing (D, E) could indicated comparable level of sensation of walking (not significantly different) with the stimulus H. This is considered due to cognitive passivity of arm swing that is not originated by own will. The passive swing might provide a unique tool for introducing pseudo activeness or agency of body motion in this aspect.

6. Conclusions

The present study investigated the characteristics of the passive arm swing display for creating the sensation of walking. The passive arm swing amplitude about 20 percent smaller than the real motion was appropriate according to the preliminary evaluation. This shows a remarkable contrast to the vestibular and proprioceptive stimulation in its amplitude setting where the amplitude is reduced to 5 to 10 percent. The real arm swing is considered to be passively established in the real walk, which is the same condition of the display. The flexion/extension ratio was shifted forward from the real walk. The sensation of walking was increased when both the vestibular and the arm swing were presented synchronously. The passive presentation of arm swing might provide a unique tool to modify activeness of body motion.

Acknowledgment

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