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Effect of Sensory Manipulations on Human Joint Stiffness Strategy and Its Adaptation for Human Dynamic Stability

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***Abstract*—**Sensory input plays an important role to human posture control system to initiate strategy in order to counterpart any unbalance condition and thus, prevent fall. In previous study, joint stiffness was observed able to describe certain issues regarding to movement performance. But, correlation between balance ability and joint stiffness is still remains unknown. In this study, joint stiffening strategy at ankle and hip were observed under different sensory manipulations and its correlation with conventional clinical test (Functional Reach Test) for balance ability was investigated. In order to create unstable condition, two different surface perturbations (tilt up-tilt (TT) down and forward-backward (FB)) at four different frequencies (0.2, 0.4, 0.6 and 0.8 Hz) were introduced. Furthermore, four different sensory manipulation conditions (include vision and vestibular system) were applied to the subject and they were asked to maintain their position as possible. The results suggested that joint stiffness were high during difficult balance situation. Less balance people generated high average joint stiffness compared to balance people. Besides, adaptation of posture control system under repetitive external perturbation also suggested less during sensory limited condition. Overall, analysis of joint stiffening response possible to predict unbalance situation faced by human.

***Keywords*—**Balance ability, joint stiffness, sensory, adaptation, dynamic.

I. INTRODUCTION

WEAKENED in sensation of lower extremities, visual acuity and vestibular response are not uncommon among elderly, and it may increase a risk of fall which sometimes can lead to death [1], [2]. Sensory inputs play an important role for human posture control system to initiate strategy for counterpart any unbalance condition and then, stop us from fall. Perturbation or disturbance senses by sensory system lead central nervous system (CNS) to decide an appropriate balancing strategy neither limits nor initiates movement at any parts of the body where it may be seen through joint stiffness.

In previous research, investigations on joint stiffness characteristic have shown its response towards some movement performance issues. Joint stiffness strategy would act to correct center of pressure (COP) to move in the same direction as center of mass (COM) to maintain in balance position [3]. Besides, the study of gait performance on osteoarthritis's patient suggested that defected joint is stiffer than other parts [4]. Furthermore, research by Fitzpatrick et.al (1992) concluded that posture sway confine when reflex response was higher especially during sudden disturbance, which lead body part to stiff [5]. Thus, those findings indicate that imbalance makes patient generate high joint stiffness and have shown it is relevance to be used detect weakness in stability. However, a focus studies on joint stiffness properties to define imbalance is still less.

Furthermore, human balance characteristic or human posture strategy usually represent as an inverted pendulum model. Inverted pendulum model has been beneficial to describe postural sway and it is used widely in analysis of posture control system. Joint stiffness has become one of the important parameter in the model as a feedback in most of them [6], [7]. Estimation of joint stiffness amount using linear regression of moment-angle was reported to give a limited input on active component of stiffness characteristic, thus needs further investigation [8]. It is believed that active - passive component of balancing behavior can be observed under repetitive work [9]. Besides, characteristic of joint stiffness under different type of perturbation and sensory input condition are still less discussed.

Thus, this study aims to identify effects of sensory manipulations and different type of perturbation on posture control system especially, joint stiffness and its adaptation over repeatable perturbation. Based on these, the relationship between joint stiffness response and balance ability can be defined. Thus, a reliable model to present posture control system can be built.

II. PROCEDURE

A. Subjects

In this study, seven healthy young subjects (aged 24.24± 2.19 years old) were participated. Each subject provided informed written consent prior participation.. Information regarding to subject's history of falls and physical condition was recorded as reference.

B. Experiment Set Up

Subject was exposed with two type of external perturbation which were forward-backward and tilt up-tilt down with displacement of 70mm and 6º respectively at four different frequency (0.2, 0.4, 0.6 and 0.8 Hz). These perturbations were produced by movable platform (MB-150, COSMATE,

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JAPAN) while their vision (eyes-closed (C) and eyes-opened (O)) and head movement (N) were manipulated. By fixing the movement of neck and head to body using neck collar (ADFIT collar, ADVAN FIT), it is believed that vestibular system will not able to sense changes in surface orientation precisely [10]. Both kinetic and kinematics data was collected using motion analysis (HWK-200RT, Motion Analysis, USA) and force plate (9286A, KISTLER, JAPAN). Each trial (*two type of perturbation*four type of sensory manipulation combination *four different frequency*) was recorded for 60s with a locked knee joint (using splint) to prevent bias movement from knee. Before the experiment started, all subjects were undergo Functional Reach Test (FRT) to evaluate initial balance score [11].

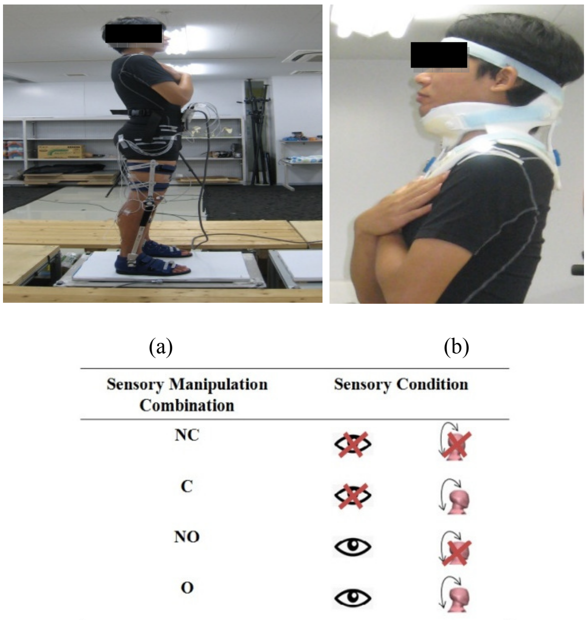

Fig. 1 (a) Subject preparation for experiment (b) The use of neck collar to limit head movement (c) Explanation on sensory manipulation combination

C. Statistical Analysis

All data were analyzed using mean and standard deviation. All results were described in average of 60s. Comparisons between conditions were done using Two Way ANOVA and Pearson correlation coefficient.

D. Measurement of Joint Stiffness

Joint stiffness was measured based on inverted pendulum model as shown below. Stiffness (K) at joint can be defined as (1) below;

$$K = \frac{\tau}{\theta} \quad (1)$$

where τ is torque of ankle and θ is angle of joint sway. The Fv which is a vertical ground force gather from force plate data is assuming to be as follow;

$$Fv \approx m_1 g \quad (2)$$

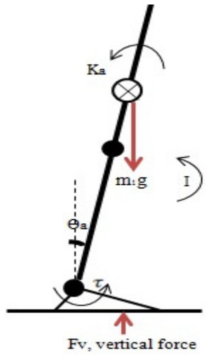

Fig. 2 Free body diagram to measure ankle stiffness based on inverted pendulum

III. Results

A. Joint Stiffness under Different Condition of Perturbation and Sensory Manipulation

As mentioned, before the experiment, subject was asked to perform a conventional clinical test which is the FRT to evaluate their actual balance ability and also their physical conditions. The details are shown in Table I. The FRT's score was observed to be negatively correlated with joint stiffness value (r^2>-0.2) as joint stiffness increase for subject with the lowest score (Table I). This indicates that people with low balance ability tends to stiff their joint more to maintain balance position under dynamic perturbation condition. However, these correlations were weak. It might be due to the nature of the FRT test where it was conducted during quiet stance without any external factors meanwhile joint stiffness analysis was examined during perturbed standing.

TABLE I
Comparison between Average Joint Stiffness at 0.2 Hz of Perturbation with FRT's Score

Subject No.	FRT's score (cm)	Tilt up-tilt down (Nm/rad)		Forward-Backward (Nm/rad)	
		ankle	hip	ankle	hip
1	28	672.78	206.15	472.10	212.51
2	30	132.58	105.41	65.68	104.58
3	34.9	74.42	71.16	91.66	69.43
4	38.9	277.83	31.23	236.93	79.23
5	42.63	312.68	211.14	258.89	217.33
6	45.6	206.36	88.97	193.34	94.04
7	46.73	147.67	88.93	138.07	91.00
Correlation coeff. (r^2)		-0.41	-0.25	-0.26	-0.24

The comparison was done between FRT's score and joint stiffness by using Pearson Test.

By manipulating the type of perturbation, it is believed that it is able to manipulate the proprioception system. Tilt up-tilt down and forward-backward type of perturbation did triggered different joint stiffness strategy. Based on Table I, ankle joint is more stiff during tilt up-tilt down while hip joint is stiffer during forward-backward movement. However, no significant

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different found ($p>0.05$).

According to Fig. 3, limitation of vision sensory (NC and C) produced highest ankle joint stiffness especially during tilt up-tilt down. Meanwhile, for the forward-backward perturbation, the highest ankle stiffness was observed when head movement was being constraint (NC and NO). Overall, hip joint stiffness is higher during head motion constraint condition during both types of perturbation (NC and NO). Besides, the increase of perturbation frequency did increased joint stiffness especially at ankle ($r^2>0.5$). But no significant different was observed between sensory manipulation conditions at ankle joint.

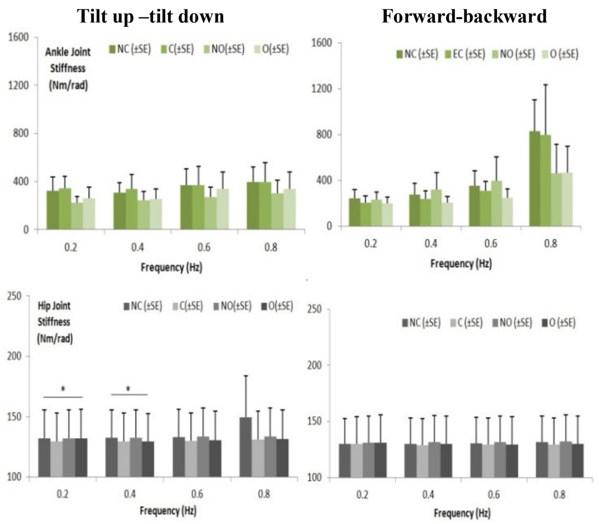


Fig. 3 Joint stiffness under four different frequency of perturbation (±SE)(*first row*: ankle, *second row*: hip) with four different sensory limitations (NC=eyes closed with neck collar, C=eyes closed, NO=eyes-opened with neck collar, O=eyes opened)(*: $p<0.05$)

B. Adaptation of Joint Stiffness over Repeated Perturbation and Limited Sensory Conditions

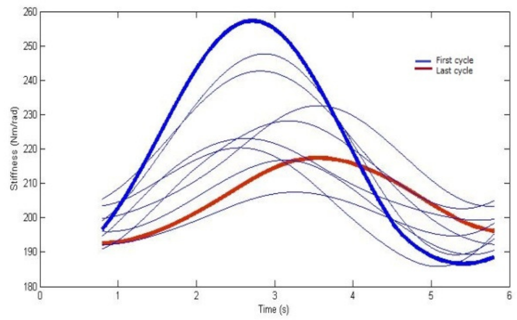
In order to evaluate the adaptation of CNS towards stiffening strategy over repeated perturbation, we compared stiffness response of each cycle of 0.2 Hz trial. During this low intensity of perturbation, it is easy to determine the effect of sensory input modification towards stiffening adaptation strategy. Adaptation of CNS towards the joint stiffening response is determined by measuring area under graph (AUG) using trapezoidal rule using (3) and (4).

$$AUG = \int_{1}^{t} K(t)\ dx \tag{3}$$

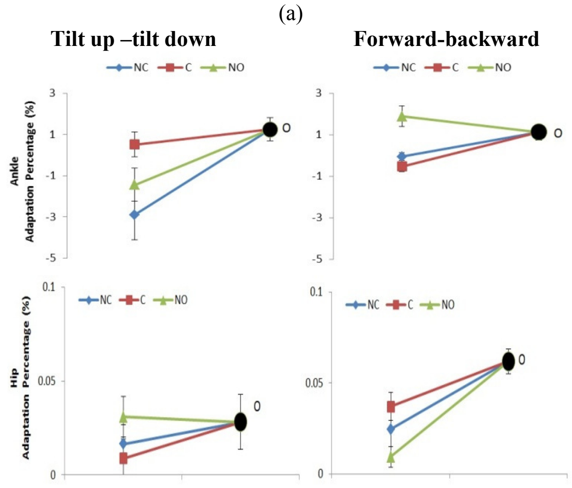
$$Adaptation\ (\%) = \frac{AUG_i - AUG_{(i+1)}}{AUG_i} x\ 100\% \tag{4}$$
$$i = 1,2,3 \ldots.$$

where K (t) is joint stiffness along perturbation period, t is time for one cycle of perturbation, and i is number of cycle

In this analysis, each cycle of joint stiffness was compared with cycle before it. Based on Fig. 4, in average, adaptation of the CNS through ankle joint stiffness was almost 1.5% (±SE) which means that during normal condition (O), healthy young subject reduces joint stiffness by 1.5% at each cycle of repeated movement. But under weak sensory input condition, subjects almost unable to adapt and joint stiffness was keep increases in order to remain balance (less or negative (-ve) adaptation percentage). Meanwhile, for hip joint, adaptation percentage was smaller than ankle but it was still able to indicate that limitations of sensory input also reduced the percentage of adaptation. However, there were no significant different found between different sensory manipulation condition ($p>0.05$).



(a)



(b)

Fig. 4*Top*: (a) Ankle joint stiffness at each cycle during 0.2 Hz. *Bottom*: (b) Comparison of average adaptation percentage of joint stiffness between normal (O) and sensory condition (±SE)

IV. Discussion

The results have shown that joints stiffness at both ankle and hip joints were able to define the balance ability of human. Where, higher value of stiffness was required by less balance people and while faced a difficult conditions. On the other hand, different types of perturbation and sensory limitations will also generate different joint stiffening strategy as expected.

Visual input plays an important role in balancing process where ankle joint was measured to be higher during eyes closed (C) at both perturbation and all frequencies. However, ankle joint stiffness was higher during NO than O when forward-backward perturbation was applied. This suggested that head and neck segment is important during high acceleration of posterior and anterior movements. During forward-backward perturbation, the COM and COP of human body were moved intensively forward and backward as the body was observed to sway more. Without movement at the head and neck segment, balance condition will become worst. This is because an otolith organ which important to detect change in acceleration is being disturbed. Moreover, the results show tilt up-tilt down perturbation did not cause large body sway than forward-backward. However, limited head motion seems to improved balance during different surface's level as subjects decreased their joint stiffness.

In determining the CNS adaptation, it is believed that weakened in sensory inputs did affect the motor learning process where, subject faced difficulty to maintain their position. They need to continuously generated force to produce stiffness by increasing muscle effort to maintain their balance along trial period. Analysis of stiffness adaptation over different types of perturbation also can detect the situation where subjects felt less balance and how ankle and hip joints working with each other to create synergy strategy between them. On the other hand, analysis on adaptation percentage has shown that joint stiffness was also an active component at initial stage of perturbation. Then, it shifts to passive behavior following the platform and was altered according to information received by the subject. Less sensory information due to certain factors (i.e., impairment, disease, ageing and etc.) will lead to reduce in adaptation.

This study has faced some limitations, firstly, the ability of the FRT test to relate with balance ability under perturbed stance. In general, the FRT describes balance ability through capability of a person to reach forward distance as far as possible which represents by COM maximum displacement. However, result from this test is very limited. Furthermore, effect of the use of neck collar to limit the head movement and thus, disturbed vestibular function is still not evident. It was observed to influence more on vision input as it permit a limited visual space (subject reported unable to see anything at below).But, the result of average stiffness have shown that it able to distinguish between sensory limitation condition.

V. Conclusion

In this study, the effects of vestibular system’s and vision’s input limitations did affect the joint stiffening strategy. Besides, it is acceptable to said that people with less balance ability tends to have high stiffness at both hip and ankle joints. Adaptation percentage of the CNS over repeated perturbation shows that healthy people were able to adapt much better compared to those who faced weakness in their sensory inputs. Further analysis especially related muscle activation and posture control system synergy will be proposed to determine their response under unbalance condition.

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