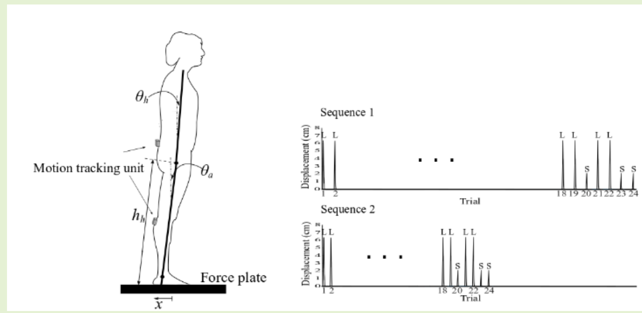
Responses to external repeated perturbations vary with time intervals

Dongwon Kim and Jong-Moon Hwang

Abstract— **Objective: We investigate postural responses that could vary with the interval of perturbations, probably leading to different contributions of relevant learning substrates. Design: A total of 12 male volunteers with no neurological deficits (age: 33.33±3.12 S.D.) experienced a sequence of perturbations. Two sequences of perturbations in the anterior-posterior direction were designed and administered: the first sequence consisted of 24-time repeated perturbations with an interval of 5 seconds, while the second sequence consisted of ones with an interval of 2.5 seconds. A perturbation of a smaller magnitude was inserted into each sequence as a catch trial. Results: The magnitude of the excursions of the center of pressure (COP) and ankle angle in response to perturbations with a longer interval is greater in comparison to that with a shorter interval (P < 0.05). A difference in responses to the perturbation following the catch trial appears in COP (P < 0.05), not in ankle angle (P > 0.05). Conclusion: The refinement of the anticipatory neuromotor system for a newly trained response can be modulated with stimulus intervals.**



Index Terms— **Center of pressure; External perturbation; internal model; postural control;**

I. Introduction

FALLS and fall injuries are a serious problem, in particular among older adults [1]. While injuries are the most obvious consequence of falls, fear of falling may lead to functional decline which may be associated with fall risk [2]. Perturbation training that involves applying an external force to an individual has been shown effective in reducing fall risk [3], [4]. In particular when coupled with typical physical therapy, such training significantly reduces injurious falls [5]. Those training programs are considered to improve anticipatory and compensatory postural adjustments [6],[7]. Various modalities have been utilized to apply a postural perturbation using mechanisms, including a translating platform [8], pulling a cable attached to an individual's waist [8], sternal nudge [9], and release-from-lean [10]. The relationship between perturbation training and fall risk appears correlated, despite barriers to clinical adoption.

Though perturbation training is beneficial for the betterment of postural control, it is unclear whether the interval of perturbations affects motor response, and eventually modulates the effect of perturbation training. The central nervous system (CNS) enables us to adapt ourselves to a series of external stimuli and reach homeostasis[11]–[13]. The central control device in the CNS is continuously reprogrammed and refined towards the way that motor outputs become optimal in response to external stimuli[14], [15]. We observed that while the body response has large variability in response to inexperienced stimuli, it shows smaller variability in response as adaptation continues, suggesting that the CNS works to find an optimal solution to regain stability from the stimuli [14], [15].

While it became obvious that our body goes through a learning process for adaptation to motor activity, motor response can vary depending on time intervals of training. Indeed there is plenty of evidence that different frequencies of training lead to involvements of different types of learning or learning in different neural substrates [16]–[18]. Several studies showed that there exist the optimal intervals that lead to the best consolidation and retention [19]–[21]. A certain time interval enhances the effect of motor learning, prolonging motor memory. While some argued that enough time intervals between trainings is necessary to consolidate motor memory [19], [21], some asserted that long time intervals can result in time decay of motor memory [22], [23]. It might be beneficial to determine the optimal time interval according to the type of the task to be trained in order to maximize the effect of motor training.

Responding to timely-dense external stimuli and refining the internal models also depend on the intervals of the stimuli. Taking finger sequence responding tasks for example, studies revealed that a longer interval between stimuli leads to a greater

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learning effect [24]. Longer intervals allow participants for time to accumulate explicit knowledge on the sequence and encode it into the CNS responding to the stimuli. The accumulated explicit knowledge in addition to implicit learning that lacks awareness results in faster responses and enhanced learning effects in tasks where the anticipatory factor is pronounced. Either the so-called implicit learning or explicit learning can be involved predominantly according to the frequency of stimuli, facilitating different neural substrates for learning [16]–[18]. Again we could humbly speculate that different time lapses of motor activity lead to involvements of different types of learning or learning in different neural substrates or learning mechanisms.

In this study, we had participants with no neurological disorder experience two types of a series of anterior-posterior translational perturbations. The two types were differentiated by the interval of perturbations. We investigated if/how intervals of perturbations modulate motor responses in terms of the center of pressure (COP) and ankle/hip excursion. It could be hypothesized that automatic postural responses that are typically made from the association between online feedback and feedforward control are influenced by intervals of repeated perturbations. While online feedback enables the CNS to perceive the environment in real time, muscle activation is centrally modulated through an anticipatory manner to recover postural stability as trials advance, which is a product of learning [14], [25]. Typically, continuous movement tasks are assumed to rely more on implicit learning, in comparison to discrete tasks including finger sequence responding, due to relative difficulty of recognizing and encoding errors into the control system [26]. Allowance of time for participants to be consciously reminded of a continuous response in a repeated task would bring about involvements of different neural learning regions. Accordingly, we hypothesize that responses would be distinguished.

II. Methods

Participants

We recruited a total of 12 male volunteers with no histories of neurological or motor deficits, from Kyungpook National University (age: 33.33±3.12 standard deviations (SD); height: 172.92±4.44 cm; weight: 71.25±8.08 kg). None of the participants were aware of our experimental design. All participants gave written informed consent to participant in the study. This study was approved by Kyungpook National University's Institutional Review Board.

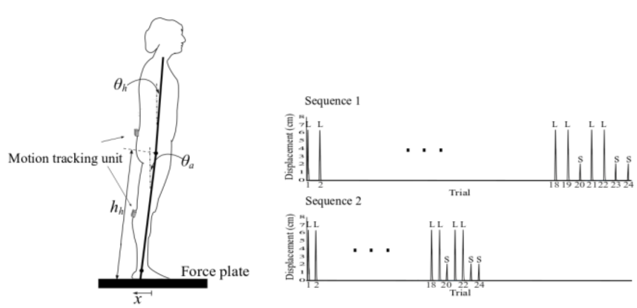

Fig. 1. A schematic of the experimental setup and definitions of the ankle angle q and hip height h. Sequence 1 and Sequence 2 consist of 19 large perturbations followed by followed by one small perturbation, 2 large perturbations, and 2 small perturbations. The perturbation interval between perturbations of Sequence 1 is set as 5 seconds, while that of Sequence 2 was set as 2.5 seconds.

Apparatus

The experimental setup was the same as one performed in a previous study [14]. Here, we re-elaborated: The experimental setup consisted of a platform on which participants stood, a miniature motion tracking device, and a personal computer (PC) running Windows 10 (Microsoft Corp. Redmond, WA, USA). The platform was built with a force plate (EzForce Plate, i2A systems Co., Ltd., Daejeon, Korea) to be used for measuring COP on a linear guide rail (8 mm/revolution) that converted a brushed DC motor's (RE65, Maxon Motor, Sachseln, Switzerland) rotary motion into anterior-posterior translational motion. We designed two kinds of perturbations that caused body sway in the sagittal plane: small and large perturbations. While the small perturbation was designed to produce a displacement of 2 cm for 0.3 s, the large perturbation generated a displacement of 6 cm for 0.3 s. The force plate was designed to immediately move back to the original position for 0.3 s. The design of these perturbations was believed to elicit a muscular and biomechanical response to the perturbations.

The motion tracking unit (MPU9250, InvenSense Inc., San Jose, USA) measured the acceleration values of the lower body, in the anterior-posterior, a_{AP}, craniocaudal (a_{CC}) and lateral (a_L) directions. A 3D printed case included each of the tracking units to allow firm placement of these units on the participant's body aligned in the three directions. The unit was attached at 5% of the total height below the knee joint. Acceleration values were used to calculate the dynamic angles of the lower body and upper body with regard to the vertical line, which were regarded as estimates of the ankle angle and hip angle, respectively, using the following equation [14], [27]:

$$\theta = tan^{-1}\left(\frac{a_{AP}}{\sqrt{a_{AP}^2+a_L^2}}\right). \tag{1}$$

Note that a_{AP} reflected the acceleration resulting from the anterior-posterior translational motion of the platform. But this acceleration component was cancelled out in the computation (1), so that it did not significantly distort the estimates of the angles. Data including the DC motor angle, COP and body acceleration were acquired at a sampling frequency of 500 Hz. No filters were applied to the kinematic data to minimize signal distortion.

White noise was given to participants using headphones to attenuate the effect of noise from the apparatus on postural control.

Procedure

Throughout the experiment, participants stood barefoot on the force plate with their feet apart in a comfortable stance and their arms crossed over the chest. We requested participants to recover their balance once a perturbation was administered and to avoid taking a step so long as they could avoid falling. We recommended them to use the ankle strategy as far as possible, instead of the hip strategy or other strategies.

Participants experienced a practice phase and a main phase. The practice phase was designed to familiarize participants with the large and small perturbations. Participants were presented each perturbation twice. In the main phase, all participants were evenly and randomly divided into two groups. Each group experienced two sequence of perturbations administered. In Sequence 1, the large perturbation was repeated 19 times, followed by one small perturbation, 2 large perturbations, and 2 small perturbations. The perturbation interval between perturbations was set as 5 seconds. In Sequence 2, the same sequence of the perturbations as Sequence 1 was designed but the perturbation interval between perturbations was set as 2.5 seconds. One group was presented Sequence 1 and Sequence 2 in turn, while the other group was presented Sequence 2 and Sequence 1 in turn. We confirmed that all participants regained and stabilized their original posture before the onset of the next perturbation. A break time of 5 minutes was provided between the two sequences in an effort to avoid fatigue and reduce the learning effect from the proceeding sequences.

Signal post-processing and Measures

All data analyses were completed using custom software (MATLAB vR2018b, Mathworks, Natick, MA).

The levels of ankle angle and COP were adjusted to 0 at the time when the perturbations began. To extract participants' postural strategies from these data, we considered how large the deviation from their original position was (Excursion I) and in what ranges they moved in response to perturbations (Excursion II).

Excursion I was defined as the distance between the maximum deviation in COP and ankle/hip angle resulting from the perturbation and their original position before the perturbation. The maximum deviation could be regarded as the first effort to regain postural stability. Excursion II denoted the total anterior–posterior movement of COP and the kinematic data in response to the perturbation. Since COP is closely proportional to the ankle moment, Excursions I and II for COP could indicate how much ankle moment was generated to regain postural stability [14]. Also, Excursions I and II for the angles of the ankle and hip would indicate the extent of body sway caused by the perturbations.

Statistical analysis

A repeated-measures analysis of variance (ANOVA), with sequence and trial as the independent variables, was used to the evaluate performance changes across repeated measurements. If the sphericity assumption in ANOVAs was violated, then Greenhouse-Geisser adjusted p-values were used. Bonferroni post-hoc tests (pairwise comparisons) were conducted if a significant interaction effect was found. The statistical analyses were performed with SPSS version 20.0 (SPSS Inc., Chicago, USA) and the significance level was set at 0.05. All analyses were preceded by Shapiro–Wilk tests of normality and their results were employed only when normality was not violated.

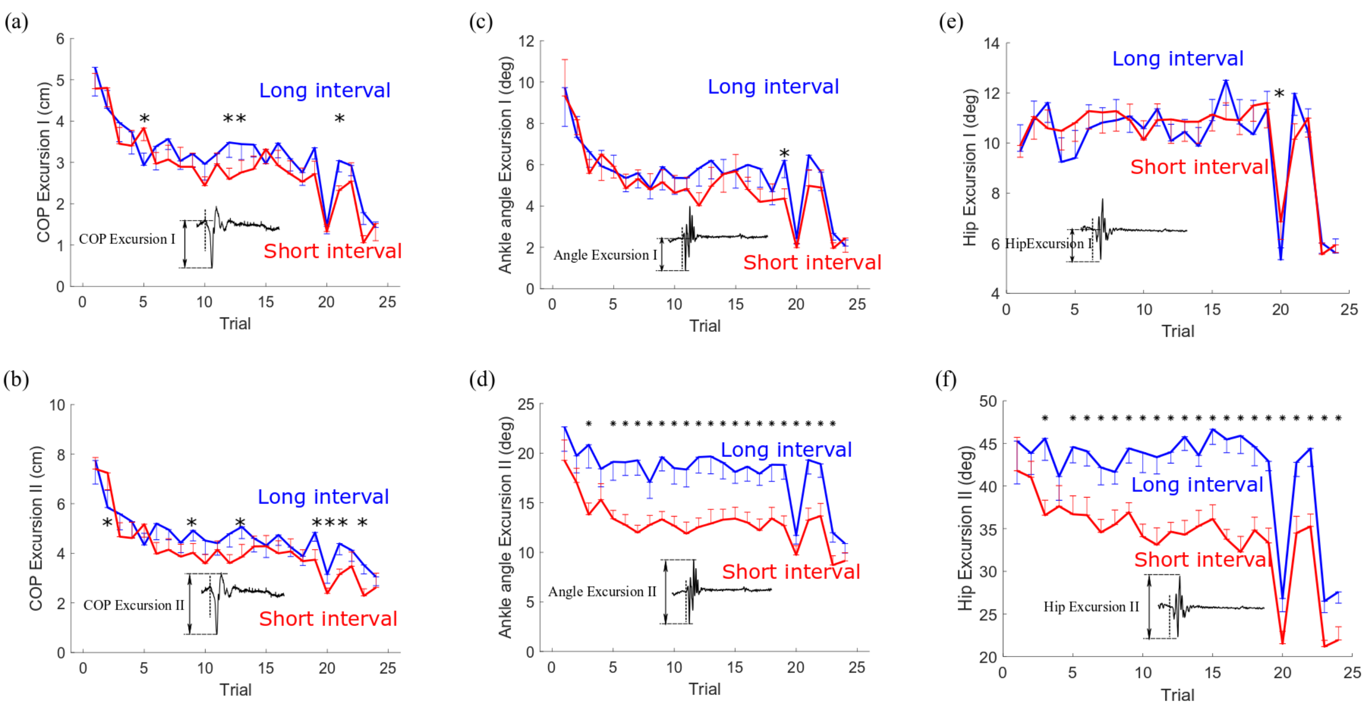

Fig. 2. Mean by sequence of the magnitudes of Excursion I and Excursion II of COP and ankle angle for Trial 1 to Trial 24 (Error bars are ± 1 standard deviation of the mean). The inlets display the definitions of Excursion I and Excursion II for COP and ankle angle. Asterisks indicate significant differences at the corresponding trials between two groups.

III. Results

Repeated-measures ANOVAs were conducted on each measure from Trial 1 to Trial 24 with trial (24 levels: Trials 1–24) and sequence (2 levels: Sequences 1 and 2) as within-subjects variables. Fig. 2 shows the overall trends of Excursion I and Excursion II of COP, ankle angle and hip angle across trials.

1. COP: ANOVA on Excursion I of COP showed a significant main effect of sequence [F(1, 11)=6.024; p=0.032; η_p^2=0.354] and a significant main effect of trial [F(23, 253)=14.808; p<0.001; η_p^2=0.574]. The interaction effect was not significant (p >0.4). The results would imply that that the sequence with a shorter interval generated a smaller Excursion I than that of a longer interval and that both of the sequences led to the learning effect. ANOVA on Excursion II of COP produced a significant main effect of sequence [F(1, 11)=11.932; p=0.005; η_p^2=0.520] and a significant main effect of trial [F(23, 253)=11.396; p<0.001; η_p^2=0.509]. The interaction effect was not significant (p>0.1). The results would also suggest that the sequence with a shorter interval generated a smaller Excursion II than that of a longer interval and that both of the sequences led to the learning effect.

2. Ankle angle: ANOVA on Excursion I of ankle angle showed a significant main effect of sequence [F(1, 11)=23.820; p<0.001; η_p^2=0.684] and a significant main effect of trial [F(23, 253)=10.335; p<0.001; η_p^2=0.484]. The interaction effect was not significant (p>0.5). The results would imply that that the sequence with a shorter interval generated a smaller Excursion I in ankle angle than that of a longer interval and that both of the sequences showed adaptation. ANOVA on Excursion II of ankle angle produced a significant main effect of sequence [F(1, 11)=17.348; p=0.002; η_p^2=0.612] and a significant main effect of trial [F(23, 253)=10.645; p<0.001; η_p^2=0.492]. The interaction effect was significant [F(23, 253)=1.648; p=0.034; η_p^2=0.130]. The results would imply that the sequence with a shorter interval led to a smaller Excursion II than that of a longer interval and that both of the sequences led to adaptation.
3. Hip angle: ANOVA on Excursion I of hip angle showed a significant main effect of trial [F(23, 230)=14.848; p<0.001; η_p^2=0.598]. No main effect of sequence and interaction effect were reported (p>0.2). The results would imply that that participants showed adaptation. ANOVA on Excursion II of hip angle produced a significant main effect of sequence [F(1, 11)=96.803; p<0.001; η_p^2=0.898] and a significant main effect of trial [F(23, 253)=16.775; p<0.001; η_p^2=0.604]. The interaction effect was significant [F(23, 253)=1.955; p=0.007; η_p^2=0.151]. The results would imply that the sequence with a shorter interval led to a smaller Excursion II than that of a longer interval and that the sequences led to adaptation.

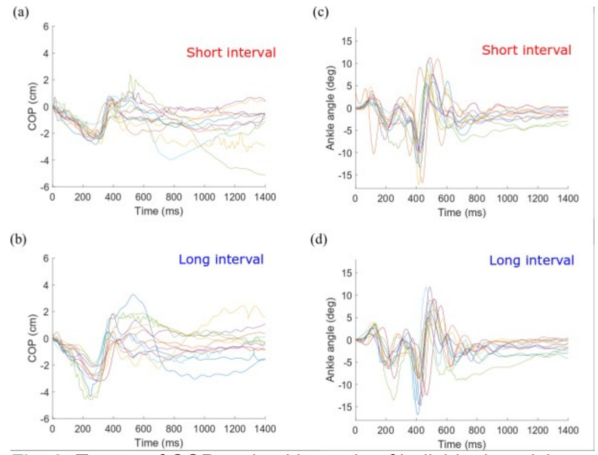

Fig. 3. Traces of COP and ankle angle of individual participants at Trial 21 for Sequence 1 (longer interval) and Sequence 2 (shorter interval).

IV. Discussion

This study tested the hypothesis that different time intervals of stimuli to postural stability lead to different responses. We revealed that a train of perturbations with shorter intervals as well as longer intervals cause adaptation or the learning effect (the main effect of trial: p<0.05), but it occurs with no significant different learning rates (interaction p>0.05), in terms of COP. Interestingly, we found that the degree of transfer of learning depends on the time interval from the significant differences between the two groups in measures (i.e. COP) at Trial 21 following a catch trial. In this section, we discuss it with supporting evidence presented by other studies.

The primitive finding of this study might be that a train of perturbations with shorter intervals results in smaller excursions of ankle angle in response. Despite perturbations with the same profile presented to the two groups, participants show different responses in terms of the degree of body sway. These results might come from the hypothetical theory that the human motor system relies on anticipatory control based on prior experiences [14]. We could interpret the results as participants tended to employ greater muscle co-contraction to minimize body sway caused by faster repetitions of perturbations. An increase in co-contraction typically occurs to minimize postural sway [28]. Increasing joint stiffness through muscle co-contraction might partially originate from fear about the fast repetition of perturbations. If we have fear when facing a postural threat, we employ a stiff ankle strategy to assure stability [29].

The results that a shorter time interval leads to a smaller excursion in COP response could also be attributed mainly to the stiff ankle strategy. It is reasonable to speculate that stiffer ankle joint through greater co-contraction between the muscles in the antagonistic setup spanning the ankle joint leads to a smaller body sway, and a smaller body sway results in a smaller excursion in COP. A larger body sway leads to a larger extent of body leaning that requires a larger torque at the ankle to upright the leaned body against gravity. These results are in agreement with those of a previous study [14]. These results are also in accordance with the empirical results of a study, though they concluded a different opinion about ankle joint stiffness [30].

The interesting finding is perhaps about the responses to perturbations in trials following a catch trial (at Trial 20). Those responses would imply the robustness of the learning effect to an unlearned stimulus. The downward COP responses demonstrate motor learning through updating the internal model. Central activation is modulated in anticipation of postural sway [31]. We could reasonably regard that the plateau of the learning effect starts at least from Trial 15 for both sequences (with different time intervals). The train of perturbations with a longer time interval exhibits a different response to Trial 21 in comparison to that with a shorter interval ($p<0.05$). While the COP at Trial 21 responses show a significant difference between the two groups, Excursion I for ankle angle does not, suggesting that the difference in ankle stiffness between the two groups is not significant. The possible reason would be that Excursion I for ankle angle reflects the extent of body sway or the extent of muscle co-contraction which is primarily affected by the very previous trial, while Excursion I for COP reflects motor responses trained through repetitions of perturbations [14]. It could be hypothesized that while contraction of agonist muscles and co-contraction of antagonistic muscle pairs across the ankle joint are employed to stabilize posture, the two components are believed to operate independently of each other. Excursion Is for COP and ankle angle are a measure made in a range where online feedback works [32]. Rather than co-contraction simply achieved through an anticipatory manner from the previous trial, perceiving the perturbation and incorporating it into the motor response (i.e. COP) might reflect the refinement of the internal model that pertains to motor responses. Excursion II for COP could also be evidence of this theory. Though significant differences at Trials 19 and 21, the p-value for Trial 21 is greater than that for Trial 19 (we believe that the significant differences for Trial 19 would not be meaningful). This could straightforwardly imply the different strengths of the learning effects of the two trains that might be linked to the degree of an effort to minimize the influence by the catch trial. That is, a longer interval leads to a stronger learning effect. The group with a longer interval tends to retrieve the response used to the perturbations following the catch trial. Responses at Trial 23 could imply a stronger learning effect of a longer interval.

Then what factor originating from the difference in interval made the difference in response between the two groups? Perhaps the difference is mainly because a longer interval allows for time to program and consolidate the motor system to respond to the perturbation. A longer interval would lead to the involvement of conscious learning that facilitates motor learning [33], [34]. As mentioned in Introduction, finger sequence learning studies found that a longer interval between stimuli leads to an enhanced learning effect [24], [34]. The possibility of the involvement of explicit knowledge in sequence learning would be the main contributor to faster responses and enhanced learning effects in tasks. Indeed explicit knowledge on learning facilitates different neural substrates during motor execution and substantially affects the formation of the anticipatory mechanism. Studies suggest that the frontal cortex and basal ganglia are related to implicit memory while the hippocampus and temporal-parietal cortex are relevant to explicit memory [16]–[18], [35]. The studies that showed that prolonged intervals degrade motor learning also evidence that the anticipatory component mainly governed by the internal model can be modulated by intervals. They asserted that too long intervals (amounting to several hours) could allow factors to intervene the formation of the internal model for trained motoric behaviors, leading to a reduction in retention. From a series of empirical evidence regarding the influence of time intervals, this study reasonably speculates that time intervals are a critical factor to building up internal models for a novel motor response.

In sum, we expect that our findings would be helpful in creating effective clinical strategies for perturbation training that aims at reducing falling.

References

[1] I. Nurmi and P. Lüthje, "Incidence and costs of falls and fall injuries among elderly in institutional care," *Scand. J. Prim. Health Care*, vol. 20, no. 2, pp. 118–122, 2002, doi: 10.1080/pri.20.2.118.122.

[2] M. E. Tinetti, D. Richman, and L. Powell, "Falls efficacy as a measure of fear of falling," *Journals Gerontol.*, vol. 45, no. 6, pp. 239–243, 1990, doi: 10.1093/geronj/45.6.P239.

[3] Y. Wang, S. Wang, R. Bolton, T. Kaur, and T. Bhatt, "Effects of task-specific obstacle-induced trip-perturbation training: proactive and reactive adaptation to reduce fall-risk in community-dwelling older adults," *Aging Clin. Exp. Res.*, vol. 32, no. 5, pp. 893–905, 2020, doi: 10.1007/s40520-019-01268-6.

[4] Y. C. Pai, T. Bhatt, F. Yang, and E. Wang, "Perturbation training can reduce community-dwelling older adults' annual fall risk: A randomized controlled trial," *Journals Gerontol. - Ser. A Biol. Sci. Med. Sci.*, vol. 69, no. 12, pp. 1586–1594, 2014, doi: 10.1093/gerona/glu087.

[5] J. D. Lurie *et al.*, "Surface perturbation training to prevent falls in older adults: A highly pragmatic, randomized controlled trial," *Phys. Ther.*, vol. 100, no. 7, pp. 1153–1162, 2020, doi: 10.1093/ptj/pzaa023.

[6] H. Arghavani, V. Zolaktaf, and S. Lenjannejadian, "Comparing the effects of anticipatory postural adjustments focused training and balance training on postural preparation, balance confidence and quality of life in elderly with history of a fall," *Aging Clin. Exp. Res.*, vol. 32, no. 9, pp. 1757–1765, 2020, doi: 10.1007/s40520-019-01358-5.

[7] S. Tajali, M. Rouhani, M. Mehravar, H. Negahban, E. Sadati, and A. E. Oskouei, "Effects of external perturbations on anticipatory and compensatory postural adjustments in patients with multiple sclerosis and a fall history," *Int. J. MS Care*, vol. 20, no. 4, pp. 164–172, 2018, doi: 10.7224/1537-2073.2016-098.

[8] J. R. Borrelli, J. Zabukovec, S. Jones, C. A. Junod, and B. E. Maki, "Age-related changes in the capacity to select early-onset upper-limb reactions to either recover balance or protect against impact," *Exp. Gerontol.*, vol. 125, 2019, doi: 10.1016/j.exger.2019.110676.

[9] M. Tinetti, T. Williams, and R. Mayewski, "Fall risk index for elderly based on the number of chronic disabilities," *Am J Med*, vol. 80, pp. 429–434, 1986.

[10] J. Borrelli, C. A. Junod, E. L. Inness, S. Jones, A. Mansfield, and B. E. Maki, "Clinical assessment of reactive balance control in acquired brain injury: A comparison of manual and cable release-from-lean assessment methods," *Physiother. Res. Int.*, 2019, doi: 10.1002/pri.1787.

[11] "Horak et al. 1997.pdf." .

[12] A. M. De Nunzio, A. Nardone, and M. Schieppati, "Head stabilization on a continuously oscillating platform: The effect of a proprioceptive disturbance on the balancing strategy," *Exp. Brain Res.*, vol. 165, no. 2, pp. 261–272, 2005, doi: 10.1007/s00221-005-2297-7.

[13] I. D. Loram, C. N. Maganaris, and M. Lakie, "Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius," *J. Physiol.*, vol. 564, no. 1, pp. 295–311, 2005, doi: 10.1113/jphysiol.2004.076307.

[14] D. Kim and J. M. Hwang, "The center of pressure and ankle muscle cocontraction in response to anterior-posterior perturbations," *PLoS One*, vol. 13, no. 11, pp. 1–19, 2018, doi: 10.1371/journal.pone.0207667.

[15] D. Kim, B. J. Johnson, R. Brent Gillespie, and R. D. Seidler, "The effect of haptic cues on motor and perceptual based implicit sequence learning," *Front. Hum. Neurosci.*, vol. 8, no. MAR, pp. 1–11, 2014, doi: 10.3389/fnhum.2014.00130.

[16] P. J. Reber and L. R. Squire, "Parallel brain systems for learning with and without awareness.," *Learn. Mem.*, vol. 1, no. 4, pp. 217–229, 1994, doi: 10.1101/lm.1.4.217.

[17] J. Yang and P. Li, "Brain Networks of Explicit and Implicit Learning," *PLoS One*, vol. 7, no. 8, 2012, doi: 10.1371/journal.pone.0042993.

[18] H. Eichenbaum, "Conscious awareness, memory and the hippocampus," *Nat. Neurosci.*, vol. 2, no. 9, pp. 775–776, 1999, doi: 10.1038/12137.

[19] S. E. Pekny and R. Shadmehr, "Optimizing effort: Increased efficiency of motor memory with time away from practice," *J. Neurophysiol.*, vol. 113, no. 2, pp. 445–454, 2015, doi: 10.1152/jn.00638.2014.

[20] J. W. Krakauer, C. Ghez, and M. F. Ghilardi, "Adaptation to visuomotor transformations: Consolidation, interference, and forgetting," *J. Neurosci.*, vol. 25, no. 2, pp. 473–478, 2005, doi: 10.1523/JNEUROSCI.4218-04.2005.

[21] S. E. Criscimagna-Hemminger and R. Shadmehr, "Consolidation patterns of human motor memory," *J. Neurosci.*, vol. 28, no. 39, pp. 9610–9618, 2008, doi: 10.1523/JNEUROSCI.3071-08.2008.

[22] H. Tanaka, J. W. Krakauer, and T. J. Sejnowski, "Generalization and multirate models of motor adaptation," *Neural Comput.*, vol. 24, no. 4, pp. 939–966, 2012, doi: 10.1162/NECO_a_00262.

[23] A. Nettersheim, M. Hallschmid, J. Born, and S. Diekelmann, "The role of sleep in motor sequence consolidation: Stabilization rather than enhancement," *J. Neurosci.*, vol. 35, no. 17, pp. 6696–6702, 2015, doi: 10.1523/JNEUROSCI.1236-14.2015.

[24] D. B. Willingham and K. Goedert-Eschmann, "The Relation between Implicit and Explicit Learning: Evidence for Parallel Development," *Psychol. Sci.*, vol. 10, no. 6, pp. 531–534, 1999, doi: 10.1111/1467-9280.00201.

[25] D. M. Wolpert and R. C. Miall, "Forward Models for Physiological Motor Control.," *Neural Networks*, vol. 9, no. 8, pp. 1265–1279, 1996.

[26] C. Yamada, Y. Itaguchi, and K. Fukuzawa, "Effects of the amount of practice and time interval between practice sessions on the retention of internal models," *PLoS One*, vol. 14, no. 4, pp. 1–17, 2019, doi: 10.1371/journal.pone.0215331.

[27] H. Griffith, Y. Shi, and S. Biswas, "A container-attachable inertial sensor for real-time hydration tracking," *Sensors (Switzerland)*, vol. 19, no. 18, 2019, doi: 10.3390/s19184008.

[28] R. F. Reynolds, "The ability to voluntarily control sway reflects the difficulty of the standing task," *Gait Posture*, vol. 31, no. 1, pp. 78–81, 2010, doi: 10.1016/j.gaitpost.2009.09.001.

[29] S. Okada, K. Hirakawa, Y. Takada, and H. Kinoshita, "Relationship between fear of falling and balancing ability during abrupt deceleration in aged women having similar habitual physical activities," *Eur. J. Appl. Physiol.*, vol. 85, no. 6, pp. 501–506, 2001, doi: 10.1007/s004210100437.

[30] T. Ersal, J. L. McCrory, and K. H. Sienko, "Theoretical and experimental indicators of falls during pregnancy as assessed by postural perturbations," *Gait Posture*, vol. 39, no. 1, pp. 218–223, 2014, doi: 10.1016/j.gaitpost.2013.07.011.

[31] N. Kanekar and A. S. Aruin, "The effect of aging on anticipatory postural control," *Exp. Brain Res.*, vol. 232, no. 4, pp. 1127–1136, 2014, doi: 10.1007/s00221-014-3822-3.

[32] D. A. Kistemaker, A. J. Van Soest, and M. F. Bobbert, "Is equilibrium point control feasible for fast goal-directed single-joint movements?," *J. Neurophysiol.*, vol. 95, no. 5, pp. 2898–2912, 2006, doi: 10.1152/jn.00983.2005.

[33] K. Miyawaki, "The influence of the response-stimulus interval on implicit and explicit learning of stimulus sequence," *Psychol. Res.*, vol. 70, no. 4, pp. 262–272, 2006, doi: 10.1007/s00426-005-0216-y.

[34] A. Karabanov and F. Ullén, "Implicit and explicit learning of temporal sequences studied with the process dissociation procedure," *J. Neurophysiol.*, vol. 100, no. 2, pp. 733–739, 2008, doi: 10.1152/jn.01303.2007.

[35] J. A. Grahn, J. A. Parkinson, and A. M. Owen, "The role of the basal ganglia in learning and memory:

Neuropsychological studies," *Behav. Brain Res.*, vol. 199, no. 1, pp. 53–60, 2009, doi: 10.1016/j.bbr.2008.11.020.