Is the room moving? - Muscle responses following visual perturbations

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***Abstract*—Postural adjustments are essential for balance control and to reduce risk of falling. One emerging method to train reactive postural control consists in exposing individuals to safe and controlled destabilizing perturbations that intend to simulate changing conditions that can lead to falls. Studies using virtual reality suggest that visual perturbations engage mechanisms of motor adaptation, increase electrocortical activity and modulate balance performance. What is not yet clear is the impact of trunk and limb muscles activation on the postural adjustments responsible to maintain balance control. This paper aims to map the response of trunk and limb muscles to visual perturbations, and compare them to those of physical perturbations. Additionally, our study includes vertical perturbations (i.e. balance disturbances in the vertical plane) known to be a major cause of falling. Therefore, this paper also compares muscles responses to both horizontal and vertical perturbations. Fourteen healthy participants (ten males; age: 27±4; BMI: 23.8±2.6 kg/m^2) stood on a moveable platform within a virtual reality system projecting visual scenes over a 360° dome-shaped screen such that the participant appeared to be standing in the middle of a room. Concomitantly, the electrical activity of tibialis anterior, gastrocnemius, rectus femoris, hamstring, rectus abdominis, paraspinal, external oblique and deltoid muscles was captured. Amid a larger protocol, this paper reports on randomly presented 1) visual perturbations; i.e. the virtual room moves during 0.35 seconds a distance corresponding to 14 cm in four directions (forward - FP, backward - BP, upward - UP, downward - DP), each repeated three times; and 2) physical perturbations (12cm displacement in one second) for the four directions and two sensory conditions: static camera (SC; virtual room remains static) and dynamic camera (DC; corresponding transitions in the visual scenery). We calculated three muscle activation parameters: onset latency, duration of activation, and magnitude. Separate 2-factor repeated-measures ANOVA were applied for each outcome measure across factors of perturbation direction (FP, BP, UP and DP) and condition (VIS, SC, DC). Forward visual perturbations led to longer onset latencies when compared to upward and downward visual perturbations (e.g. in the gastrocnemius: respectively, 443±56.6 ms vs. 326±39.6 ms and 334±51.1 ms, P<0.05). Duration of activation was longer following downward visual perturbations than after backward visual perturbations in the rectus femoris (respectively, 630±120 ms vs 335±81.2 ms, P<0.05). All lower limbs and the paraspinal muscles presented with a longer onset latency in response to visual perturbations in comparison to both types of physical perturbations (SC and DC) (P<0.05). The magnitude of activation following visual perturbations was smaller than both types of physical perturbations in all muscles (P<0.05). Duration of activation was also longer in the gastrocnemius following visual perturbations when compared to both SC and DC conditions of physical perturbations (P<0.05). Overall, magnitude of responses was often larger following horizontal perturbations in comparison to vertical perturbations. Our results suggest that visual perturbations alone activate limb and trunk muscles. Although perturbation direction seems to regulate the timing of response following visual perturbations in some limbs muscles, no differences were observed in the magnitude of activation within visual perturbations. Physical perturbations significantly increased EMG responses compared with visual perturbations. Overall, horizontal perturbations often led to faster and more intense responses than vertical perturbations. Our findings that different types of perturbations lead to more or less intense muscle responses and to different activation timing may have translational benefits for the optimization of rehabilitation strategies implementing destabilizing perturbations and oriented to persons at risk of falling.**

***Keywords*—vision, posture, perturbation, virtual reality, standing**

I. Introduction

Humans frequently have to perform postural adjustments to maintain balance. This motor control task involves both the integration of multiple sensory inputs and cognitive processing [1]. Failing to incorporate sensorimotor and cognitive demands are a major contributor to falling, which may lead to accidental deaths, injury, or impaired quality of life [2]. To address this, balance and gait rehabilitation programs look for engaging people at risk of falling in reactive postural control training. One emerging training method to attain this goal is to expose individuals to destabilizing perturbations in a safe and controlled environment. These perturbations intend to simulate changing conditions that can lead to falls, such as changes in the physical and sensory conditions that test intrinsic dysfunctions due to age, injury or disease [1, 3, 4].

The manipulation of visual fields within immersive virtual reality (VR) environments can promote adaptation of postural behavior in children [5], healthy adults [6, 7] and in persons with sensorimotor deficits [8, 9]. Changing extrinsic conditions via visual perturbations generally engages mechanisms of motor adaptation [3]. During exposure to highly reliable sensory feedback, sensory prediction models can drive adaptation of motor commands [10]. For instance, visual perturbations produce significant responses of step width as well as center-of-mass position and velocity during walking tasks [2]. In addition, transient visual perturbations within immersive VR environments may increase electrocortical activity and modulate balance performance [11]. Visual perturbations can also trigger a time-frequency electrocortical response comparable to that generated by physical perturbations, although different brain areas are suggested to be involved in each type of perturbation [1].

Immersive VR systems represent one advanced tool for the design and planning of destabilizing perturbations in safe and controlled environments [1, 2, 11-14]. To optimize rehabilitation strategies that incorporate destabilizing perturbations, it is essential to map the responses they produce [2]. In particular, a proper understanding of postural control strategies requires insights on how distinct levels of contextual visual cues and visual information induce adaptation of control strategy [3, 15].

There are studies suggesting that vision might overrule other sensory inputs (e.g. proprioceptive) in response to a perturbation [16, 17]. When vision is available and a perturbation is predictable, there is a strong anticipatory activation of trunk and leg muscles, in contrast with the lack of anticipatory activity in the case of unpredictable perturbations [18]. During continuous perturbation of balance, a progressive reduction in the electrical activity of leg muscles reflects a motor adaptation process that appeared to depend, partly, on vision conditions [19].

The aforementioned studies suggest that electrical muscular activity contributes to the plasticity of vision-regulated balance control mechanisms. However, the response of limbs and trunk muscles to visual perturbations alone (i.e. without any accompanying physical change) is not fully understood, and research to date has not yet determined how electrical activation of these muscles correspond to those of physical perturbations. This study aims, first, to explore trunk-muscle and limb-muscle responses to visual perturbations, and compare them to those of physical perturbations with dynamic and static (i.e. incongruent) visual cues.

Secondly, this study includes vertical perturbations (i.e. balance disturbances in the vertical plane due to rapid, unexpected changes in the surface height) because such conditions are known to lead to loss of balance and are one major cause of falling [20, 21]. For instance, falls frequently occur due to uneven surfaces and steps and during transferring (e.g. getting in/out of bed, getting in/off, toilet, chair, and ladder) [21]. One study investigating responses to vertical-like perturbations asked participants to step into a hidden hole in a walkway and suggest that anticipatory states may modulate reactive muscle responses [22]. Other potential sources of vertical perturbations are those triggered by the disturbance of standing balance during public transportation, as in a moving bus or subway. Such perturbations may potentially lead to falls that represent a major cause of morbidity [23].

Despite previous studies demonstrating that loss of balance is often related to vertical perturbations [20, 21], research has historically focused on horizontal perturbations. Therefore, this paper also compares responses to both horizontal and vertical perturbations.

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II. METHODS

A. Participants

Healthy young adults (20-40 years old) participated in the study. Exclusion criteria were orthopedic or neurologic conditions or any other condition (e.g. chronical illness, recent hospitalization/surgery) leading to serious mobility limitation or restriction (e.g., chronic knee pain). The Institutional Regulatory Board of the Sheba Medical Center approved this study. Prior to entering the study, all participants provided written informed consent.

B. Equipment

A fully immersive virtual reality system (CAREN High End, Motek Medical, The Netherlands) with an embedded moveable platform projected a virtual room over a 360° dome-shaped screen, so that the participant appeared to be standing in the middle of the room (Fig. 1A). Concomitantly, an electromyography (EMG) recording system (ANT Neuro, The Netherlands) captured bipolar EMG activity in eight muscles bilaterally: tibialis anterior, gastrocnemius (lateralis), rectus femoris, hamstring (biceps femoris), rectus abdominis, paraspinal, external oblique and deltoid (medial) (Fig. 1B). Since differences were not often evident across the left and right muscles, here we report on the right-side activations.

C. Experimental procedure

Participants were standing on the platform (on the treadmill) throughout the experiment. First, they were exposed to *visual perturbations* (VIS); i.e. the virtual room moved during 0.35 seconds a distance corresponding to a platform movement of 14 cm in four directions: forward, backward, upward, downward. Perturbation intensity was comparable to that of previous studies [24, 25]. Each perturbation direction was repeated three times. The 12 resulting visual perturbations took place in random order. The first perturbation occurred following a period of 45 seconds in which the virtual room remained static. Ten seconds after perturbation, the platform came back to the original position followed by a random epoch of 5-10 seconds until the next visual perturbation.

Physical perturbations followed visual ones. Amid a larger protocol that included other conditions and tasks, participants responded to 24 perturbations (12cm displacement in one second) randomized across three repetitions for each of four perturbation directions and two sensory conditions. Perturbation directions included forward (FP), backward (BP), downward (DP) and upward (UP), each within conditions of static camera (SC) and dynamic camera (DC) visual cues. In DC conditions, equivalent transitions of the viewpoint to the physical perturbation were obtained by corresponding transition in visual scenery (e.g., in UP we will see more of the small vase behind the right plant). In SC conditions, the virtual room remained static despite the physical displacement of the platform and no visual cues were provided, thus providing incongruent visual cues.

Participants were encouraged to stay within a previously designated area over the platform, and to avoid stepping.

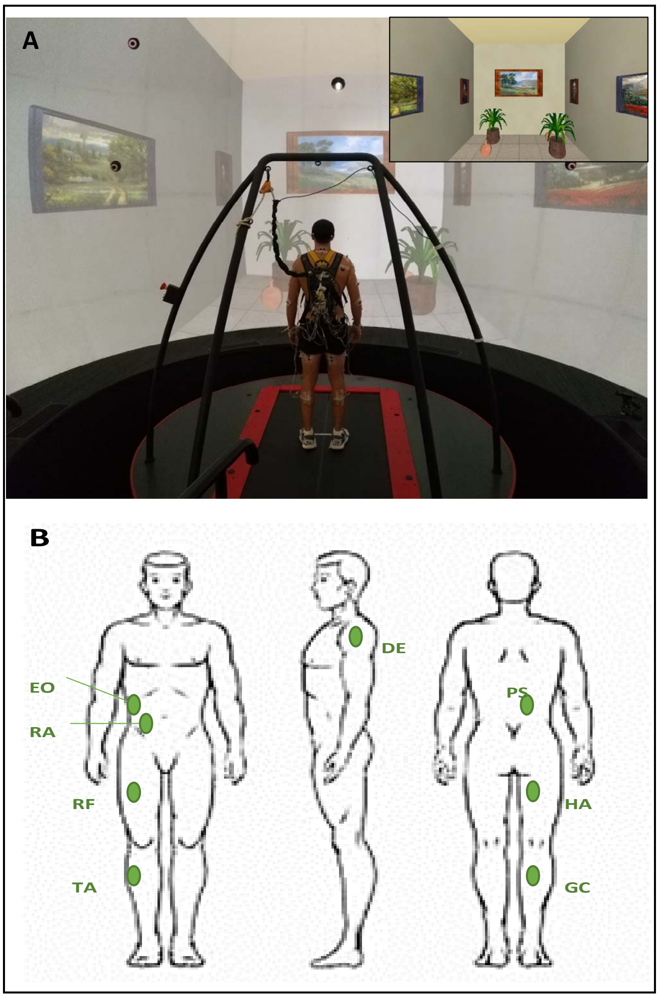


Fig. 1. Methodological setup. A) Virtual visual scenery of a simulated room. Participants stood in front of this visual scenery and were instructed to look straight ahead (into the middle of the painting hanging on the wall) and to keep balance. Objects and walls in the virtual room provide depth cues, e.g., geometrical perspectives and by the size and spatial relation between the vases and the plants. B) Depiction of the eight muscles assessed. Although they appear unilaterally in the figure, all muscles were recorded bilaterally. The electrodes' positions were determined according to SENIAM guidelines. TA: tibialis anterior, GC: gastrocnemius lateralis, RF: rectus femoris, HA: hamstring (biceps femoris), RA: rectus abdominis, PS: paraspinal, EO: external oblique and DE: deltoid medial.

D. Data analysis

We applied a filtering and rectification process on the EMG signals. A finite impulse response bandpass filter (order 500, cutoff frequencies 30Hz and 400Hz) was implemented, followed by a rectification of the filtered signal. Then, we calculated three muscle activation parameters for each combination of muscle and perturbation: onset latency, duration of activation, and magnitude. We considered a baseline of one second before perturbation and two seconds after perturbation for analysis of muscles responses. Onset latency was defined as the delay between perturbation time and the time in which the EMG signal surpasses the threshold (i.e. average of baseline + four standard deviations). For calculating duration of activation, we first obtain the maximum values (i.e. "peak") of the EMG signal during the two seconds following perturbation. We defined the end of the activation period as the time in which the EMG signal 1) crosses the peak and 2) returns to a value lower than the threshold. To estimate magnitude, we calculate the area under the curve of the EMG signal during the duration of activation. Finally, for each participant and within each muscle, we averaged the outcomes of the three repetitions of the 12 different types of perturbations (three conditions x four directions). Values were included in the average calculation only when a significant response did exist.

Separate 2-factor repeated-measures ANOVA were applied for each muscle activation parameter across factors of perturbation direction (FP, BP, UP and DP) and condition (VIS, SC, DC). We applied the Fisher's least significant difference (LSD) procedure for post hoc multiple comparison tests. We conducted statistical analyses using a numerical computing environment (Matlab; The Mathworks, USA). Unless otherwise specified, data are expressed as mean ± standard error. Statistical significance was set at $p<0.05$.

III. RESULTS

Fourteen healthy adults participated in the study (ten males, four females; age: 27±4 years; BMI: 23.8±2.6 kg/m^2). Fifty-two out of 56 visual perturbations (four directions x 14 participants) led to at least one response (out of three repetitions) surpassing baseline-based thresholds in all muscles. For SC and DC conditions, we observed a 100% response for all muscles (i.e. all participants surpassed baseline-based thresholds at least in one repetition of each type of perturbation).

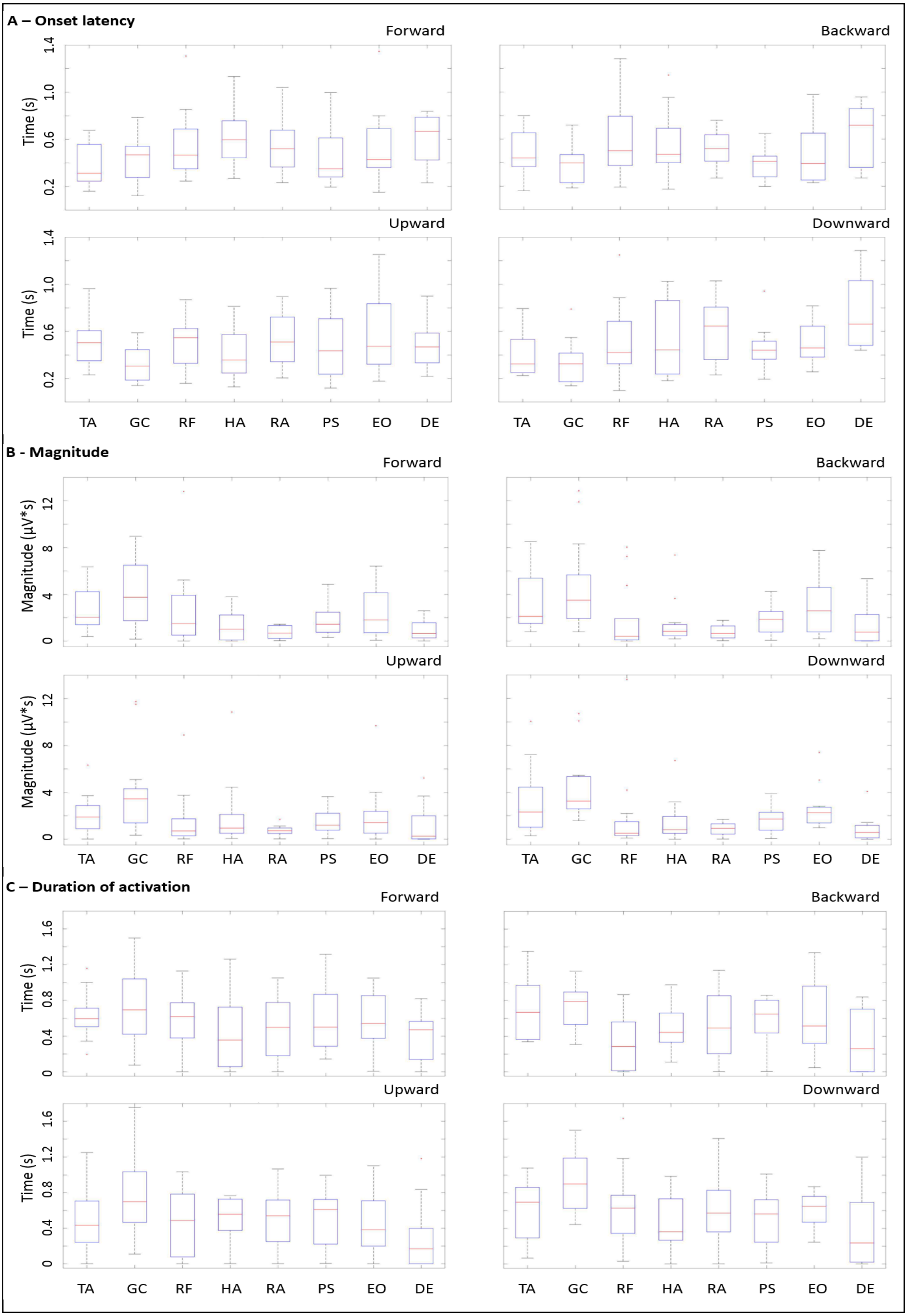
A. The effect of visual perturbations

Fig. 2 depicts the effect of visual perturbations. Forward visual perturbations led to longer onset latencies, for example, in the gastrocnemius when compared to upward and downward visual perturbations (respectively, 443±56.6 ms vs. 326±39.6 ms and 334±51.1 ms, $P<0.05$), and in the hamstring when compared to upward visual perturbations (632±73.5 ms vs. 420±59.6 ms, $P<0.05$). In turn, the deltoid exhibited a faster response following upward visual perturbations in comparison to downward visual perturbations (478±56.6 ms vs. 769±96.8 ms, $P<0.05$).

Duration of activation was longer following downward visual perturbations than after backward visual perturbations in the rectus femoris (respectively, 630±120 ms vs 335±81.2 ms, $P<0.05$). We observed no statistically significant differences in the magnitude of the response to visual perturbations among different perturbation directions.

B. Comparison of muscle responses between visual and physical perturbations

Table I includes a comparison among conditions that combines all perturbation directions. We observed that all lower limbs muscles (tibialis anterior, gastrocnemius, rectus femoris and hamstring) and the paraspinal muscles presented with a longer onset latency in response to visual perturbations in comparison to both types of physical perturbations (SC and DC) ($P<0.05$) (See Fig. 3 for a comparison of the tibialis anterior response between visual and physical-DC perturbations).



A – Onset latency
Forward
Backward
Upward
Downward
Time (s)
0.2
0.6
1.0
1.4
TA
GC
RF
HA
RA
PS
EO
DE
B - Magnitude
Forward
Backward
Upward
Downward
Magnitude (µV*s)
0
4
8
12
TA
GC
RF
HA
RA
PS
EO
DE
C – Duration of activation
Forward
Backward
Upward
Downward
Time (s)
0
0.4
0.8
1.2
1.6
TA
GC
RF
HA
RA
PS
EO
DE

Fig. 2. The effect of visual perturbations. Boxplots showing the outcomes of EMG parameters during visual perturbations for the eight evaluated muscles (right side) and within each of the four assessed directions. On each box, central marks indicate median and edges at the bottom and the top represent, respectively, 25th and 75th percentiles. Whiskers extend to the extreme data not considered as outliers (data points beyond 1.5 times the interquartile range), which are expressed through the symbol "+" in red. A) Onset latency, B) Duration of activation and C) Magnitude.

Visual perturbations also generated longer periods of activation in the gastrocnemius when compared to both SC and DC conditions of physical perturbations ($P<0.05$). The magnitude of activation following visual perturbations was smaller than both types of physical perturbations (SC and DC) in all muscles ($P<0.05$) (Fig. 3).

C. Comparison of muscle responses between perturbation directions

Table I also includes a comparison across perturbation directions that combines all conditions. In general, we observed that onset latencies following FP were faster, in particular when compared to DP that usually led to delayed responses.

In addition, we observed that magnitude was often larger following horizontal perturbations (FP particularly) in comparison to the magnitude of the responses to vertical perturbations.

IV. DISCUSSION

Our results suggest that visual perturbations alone can activate limb and trunk muscles without a physical perturbation. The perturbation direction appeared to have a role in the timing of the response in some limb muscles; however, we did not observe differences across perturbation directions in the magnitude of activation within visual perturbations. This finding is comparable to that of a previous study showing that different amplitudes of visual perturbation do not lead to significant different spatiotemporal gait responses [2]. Onset latencies in our study were longer than reported stretch reflexes (usually <100ms; e.g.[26]) which suggest balance-correcting responses and not automatic postural reactions. Responses to visual perturbations are usually driven by a perceived correction need [2]; i.e. an action that takes place in anticipation of expected congruent disturbances. Reaction to visual perturbations might be an attempt to reproduce the type of reaction expected by congruent proprioceptive information [17].

TABLE I. COMPARING EMG OUTCOMES ACROSS PERTURBATIONS

Muscle	Parameter	Condition			Direction				P
		VIS	SC	DC	FP	BP	UP	DP	
Tibialis anterior	OL (ms)	442±25.9	340±30.7	308±22.1	275±20.8	320±25.1	373±27.5	478±41.2	*, &
	DA (ms)	614±46.5	626±43.3	580±42.2	465±36.9	707±50.2	532±49.6	721±53.5	*
	MAG (µV*s)	2.81±0.32	27.6±3.60	22.8±2.7	39.8±4.85	19.1±2.49	6.51±0.86	6.94±0.90	*, &
Gastrocnemius	OL (ms)	372±24.7	351±19.9	333±21.7	344±23.7	283±19.5	320±14.6	459±32.4	*, &
	DA (ms)	774±52.8	628±48.4	620±42.7	798±46.1	556±45.5	471±60.5	862±48.3	*, &
	MAG (µV*s)	4.28±0.46	21.7±2.08	19.9±1.56	24.3±2.93	18.8±2.06	9.27±1.09	9.95±1.02	*, &
Rectus femoris	OL (ms)	543±39.8	448±32.4	402±27.6	372±33.3	497±4.04	493±34.8	487±54.7	&
	DA (ms)	503±51.5	532±38.0	508±47.5	385±37.6	600±5.09	533±57.2	540±57.8	*
	MAG (µV*s)	1.99±0.43	13.8±2.05	12.0±1.62	21.0±2.71	9.36±1.55	4.10±0.76	3.28±0.63	*, &
Hamstring	OL (ms)	535±37.5	399±39.6	369±20.0	410±34.3	372±32.2	402±30.2	544±53.9	*, &
	DA (ms)	482±41.4	485±36.8	545±43.7	468±49.6	537±28.8	450±37.3	563±53.9	
	MAG (µV*s)	1.80±0.38	10.34±1.52	9.26±1.22	11.1±2.15	8.78±1.54	4.38±0.62	4.79±0.81	*, &
Rectus abdominis	OL (ms)	558±33.5	444±28.0	512±39.3	413±36.0	543±33.5	500±37.9	560±47.9	*
	DA (ms)	531±51.0	457±38.3	441±42.9	367±38.5	596±49.3	463±54.1	474±55.9	*
	MAG (µV*s)	0.78±0.07	5.28±0.56	4.89±0.47	6.21±0.92	3.20±0.39	2.71±0.32	2.77±0.32	*, &
Paraspinal	OL (ms)	449±29.7	382±23.9	334±16.2	380±29.7	329±14.9	381±28.4	458±33.0	*, &
	DA (ms)	556±43.3	527±35.6	535±35.3	541±46.9	525±38.3	525±37.4	563±51.7	
	MAG (µV*s)	1.69±0.17	8.31±0.72	7.12±0.44	8.31±1.03	6.81±0.69	4.02±0.38	4.08±0.43	*, &
External oblique	OL (ms)	526±37.7	448±31.3	466±37.3	371±33.0	523±41.7	518±48.1	504±36.3	*
	DA (ms)	551±44.4	517±38.3	491±43.3	401±35.2	593±51.8	538±56.1	543±44.2	*
	MAG (µV*s)	2.53±0.31	11.0±1.03	10.3±0.93	11.3±1.45	7.29±0.84	6.82±1.02	6.91±0.99	*, &
Deltoid	OL (ms)	619±38.4	544±45.8	488±35.4	453±33.8	562±47.5	591±45.8	594±58.0	
	DA (ms)	348±51.0	480±43.3	441±52.0	387±51.9	447±56.8	426±61.6	443±58.8	
	MAG (µV*s)	1.10±0.21	9.18±1.54	7.37±0.86	10.8±2.34	5.50±0.73	4.45±0.61	3.83±0.50	*, &

OL: onset latency; DA: duration of activation and MAG: magnitude. *: $P<0.05$ in the comparison among perturbation direction. &: $P<0.05$ in the comparison among conditions.

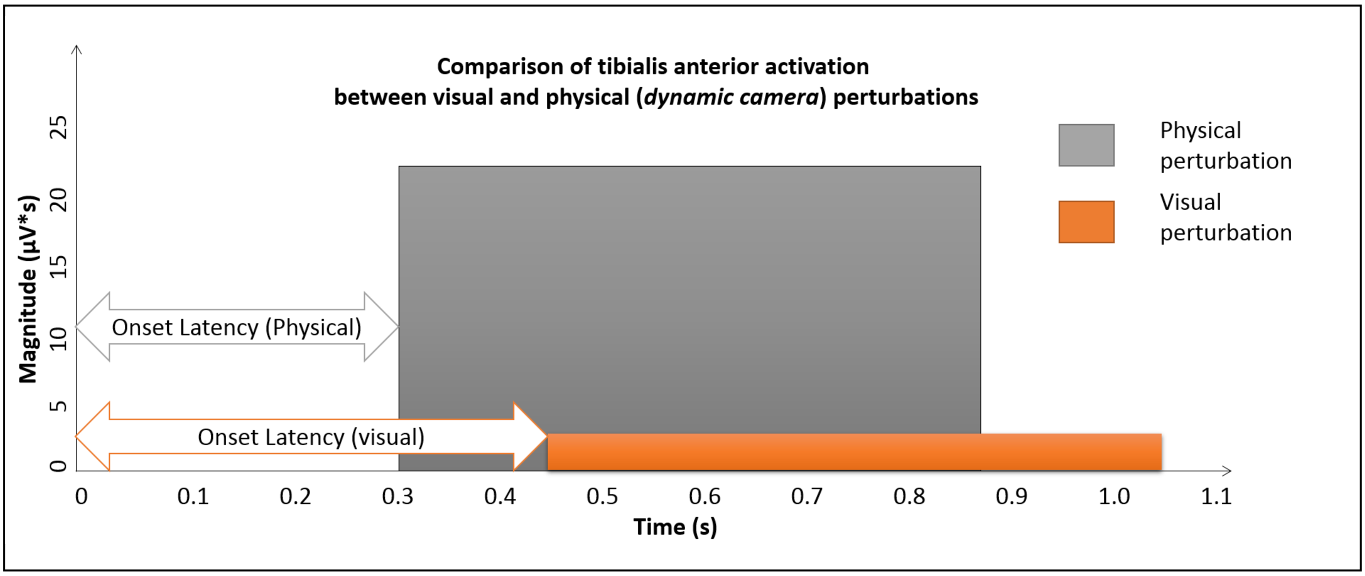


Fig. 3. Comparison between visual and physical perturbations. Rectangles represent the averaged onset latency (time from zero; i.e. zero marks perturbation time), duration of activation (shape width) and magnitude (shape height) of the overall physical perturbations (dynamic camera - gray rectangle) and visual perturbations (orange rectangle) depicting the response of tibialis anterior. The figure shows the differences between onset latencies and magnitude: visual perturbations often led to delayed, lower-magnitude responses in comparison to physical perturbations.

We observed that physical perturbations significantly increased EMG responses compared with visual perturbations. Our findings are comparable to those of a previous study showing that pull perturbations substantially increased peak EMG more than visual perturbations [1]. In another study, it was shown that while training a balance task during walking, visual perturbations led to the activation of occipital and parietal cortical regions [11]. To contribute in the design of rehabilitation protocols in patients with neurological conditions, further studies may focus on the specific neural mechanisms involved in the activation of different limbs and trunk muscles during destabilizing perturbations. Knowing these differences in the neural mechanisms of postural responses among sensory, physical, or combined perturbation conditions will be essential to understanding how to develop staged rehabilitation protocols in a virtual reality setting.

The conflict between proprioceptive information from the lower limbs in the standing person and the mismatching visual motion cues may be responsible for the observed muscle responses to visual perturbation [25]. Visual perturbations elucidates a conflict with the vestibular system as well, which differently from the visual system does not detect motion. Presumably, as suggested by other authors, there might be a visual dominance during sensory reweighting tasks [24, 25]. To trigger postural adjustments, visual perturbations would need to elicit vection for individuals to "realize" the conflict [2, 27]. Further research is needed to elucidate the neural mechanism involved in the sensory reweighting processes emerging from visual perturbations.

A. Clinical implications

Our study builds on previous studies showing that visual perturbations within immersive virtual reality environments may modulate balance performance and promote motor learning [11]. Reactive postural control interventions might consider the incorporation of perturbations similar to the ones described in our study, in particular for those patients with intact stretch reflexes and/or visual dependency [8, 28].

Our findings that different types of perturbations lead to more or less intense muscle responses may have translational benefits for the rehabilitation of persons at risk of falling. For example, due to the less intense limbs and trunk muscles responses, visual perturbations may be implemented during early stages of balance reaction therapies (e.g., when physical strength is still regained in post trauma) and can contribute to an initial evaluation/training session aiming to determine the intensity of personalized rehabilitation protocols (e.g. in patients with cerebral palsy; [9]). Physical vertical perturbations can represent a medium-intense set of destabilizing perturbations, while horizontal (in particular, forward) perturbations can be applied in later stages of balance reaction therapies.

B. Limitations of the study

We separated randomization into two stages. Participants were exposed, first, to randomized visual perturbations, and later, to randomized physical perturbations. The reason was to better identify *natural* responses towards visual perturbations, i.e. avoiding potential learning effects from previous physical perturbations. This study evaluated only young adults on a small subset of perturbation types and parameters. Further study remains needed to optimize parameters and to ascertain the responses of clinical or aging populations.

C. Conclusion

Our results suggest that visual perturbations alone induce muscle responses of the trunk and limbs. Visual perturbations often generated delayed, lower-magnitude responses in comparison to physical perturbations. Although perturbation direction did not have a differential role in the magnitude of activation following visual perturbation, it had a major contribution on muscles responses after physical perturbations. Generally, horizontal perturbations led to faster and more intense responses than vertical perturbations. Our findings may have translational benefits during the design and planning of VR-based rehabilitation of reactive balance control.

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