When mechanical engineering inspired from physiology improves postural-related somatosensory processes

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ABSTRACT

Being the first stimulated by the relative movement of foot skin and the underneath moving support surface, the plantar tactile receptors (i.e., mechanoreceptors) play an important role in the sensorimotor transformation giving rise to a postural reaction. In this light, a surface (i.e., biomimetic) complying with the characteristics of the mechanoreceptors and the skin dermatoglyphs (i.e., pattern of the ridges) should facilitate the cortical processes in response to the somatosensory stimulation involved in the balance recovery motor control.

Healthy young adults (n = 21) were standing still either on a biomimetic surface or on two control surfaces (i.e., grooved or smooth), when a sudden but low acceleration of the supporting surface along the lateral direction was triggered. A shorter and greater robust evoked somatosensory response (i.e., SEP) was observed when participants were standing on the biomimetic surface. As well, a lower oscillatory response in the time-frequency domain, including a theta response (5–7 Hz) in the left posterior parietal cortex (PPC), was recorded with the biomimetic surface. The observed higher shear forces induced by the interaction between the feet and the biomimetic surface, during the displacement, was likely at the origin of the increased SEP. Besides, the decrease of theta power suggests that the balance task became less challenging. This interpretation was tested in a second experiment by adding a cognitive task, which should be less detrimental for the postural reaction in participants standing on a biomimetic surface. According to that hypothesis, an efficient postural reaction (i.e., shorter latency and greater amplitude) was observed for the biomimetic surface.

Introduction

During everyday life, unpredictable circumstances can challenge our equilibrium in different directions while standing. This occurs for example when standing passengers are subjected to unexpected acceleration and braking manoeuvres in public transport. Exquisitely compliant, the skin of the foot sole is deformed even before the passenger's reaction to the driver's manoeuvres. This skin deformation is due to the mechanical interaction (i.e., shear forces) generated by the surfaces in contact (i.e., the skin of the feet and the supporting surface) and the gravity force acting on the body mass (i.e., body weight). Although the shear forces are small relative to the weight force during natural quiet standing, they are readily detectable by the tactile receptors (Morasso & Schieppati, 1999). These shear forces, and the consequent skin transient deformations, activate the mechanoreceptors located in the skin allowing the brain to identify the direction and amplitude of the perturbation, before being detected by other sensory inputs (e.g. visual, vestibular, or proprioceptive, Mouchnino et Blouin 2013). Inputs from these tactile receptors also contribute to define the limits of postural stability (Carpenter et al., 2010; Latash et al., 2003; Mochizuki et al., 2006; Murnaghan et al., 2011; Riley et al., 1997) to shape the postural responses to counteract balance perturbations.

The low perceptual threshold for detecting small acceleration of the support surface (e.g., down to 0.14 m/2 in Mouchnino et Blouin 2013) suggests a great responsiveness of the tactile sensory system. This responsiveness could have a twofold origin. First, it could stem from the richness of the receptor types (fast and slow adaptive, type I or II for the main tactile receptors) and from the characteristics of the receptors' receptive fields (round to oval in shape, extended or small, with sharp or blurred boundaries) (Kennedy & Inglis, 2002). It could also stem from the great compliance (i.e., deformation) of the skin in which the receptors are embedded, which depends, among others, on the footprint (epidermal ridges) orientation. The different fingerprint orientations, relative to the textured surface, enhance the subsurface strain and transmission of tactile information for any direction of the shear forces (Fearing et Hollerbach 1985; Prevost et al. 2009). The mechanoreceptors and footprint spatial characteristics therefore optimise skin deformation, neural encoding of this deformation and transmission of cutaneous sensory inputs.

While the interaction between a surface and the skin has been extensively studied during finger exploration of a surface (e.g., Hollins et Risner 2000; Lederman et Klatzky 2009; Camillieri et al. 2018; Massimiani et al. 2020; see for review Basdogan et al. 2020), intriguingly, most of the investigations in the field of balance control have ignored the surface/body contact mechanics. This is particularly surprising given that the foot soles show

footprints (dermatoglyphs) that have similar types and density of forms as fingerprints (e.g., ~60% of loops are shared by fingerprint and footprints, Sarma 2020). Skin deformation during tactile exploration depends not only on the morphological, topographical, and mechanical properties of the skin, but also from the physio-chemical properties of the surface (i.e., materials, topographic features such as height differences, adhesion, spatial period, … Cornuault et al. 2015). In this light, one can hypothesise that the processing of foot cutaneous inputs could be enhanced when standing on a biomimetic surface, whose texture is inspired by the spatial characteristics of both mechanoreceptors and dermatoglyphs.

To specifically test this hypothesis, the amplitude of the cortical evoked somatosensory potential (i.e., P_1N_1 SEP) has been here recorded and compared when the participants were standing either on biomimetic or control surfaces, which translated in the lateral direction. Because it witnesses the amount of sensory input processed at the cortical level (Desmedt & Robertson. 1977; Hämäläinen et al. 1990; Salinas et al. 2000; Lin et al. 2003; Case et al. 2016), the amplitude of the P_1N_1 SEP component was expected to be greater when the participants stand on a biomimetic surface than on other types of surface (e.g., smooth) *(Experiment 1*). Furthermore, the facilitated integration of the perturbation-related sensory information (e.g., somatosensory) should be observed (after thalamic relay) by an increase activity of a distributed network involving primarily S1 and later, S2 and the posterior parietal cortex (Hämäläinen et al., 1990; Mauguière et al., 1997).

Moreover, since the efficiency of the sensory processes allow a better detection of balance threats, the use of a biomimetic surface should decrease the cognitive demand associated to equilibrium maintenance during support surface translation. To test this hypothesis, we compared the changes in the cortical theta band power (4-7 Hz) evoked by the translation of the biomimetic and control surfaces. Indeed, recent studies have shown that an increased theta power is an electrophysiological biomarker of the increased difficulty of the balance task. For instance, Sipp et al. (2013) found that significant increases in theta band power in the left sensorimotor cortex was associated with an imminent rightward or leftward loss of balance. Afterwards, this increase in theta band power was widespread in different other cortical areas (e.g., anterior parietal and anterior cingulate areas). Similar increase of theta band activity was observed during the preparation of a challenging balance recovery (keeping the feet-in place) rather than stepping, when the postural response was known in advance (Solis-Escalante et al., 2019). More specifically, the posterior parietal cortex (PPC) seems to be a key region where increasing theta band activity was observed on the transition from a stable to an unstable surface (Hülsdünker et al., 2015; Mierau et al., 2017). This is in line with de Lafuente et Romo

(2006) recordings of neural responses to tactile stimulation in Monkey, which appear (~60ms) in the superior parietal cortex following neural responses within the primary sensory areas (S1). Since the PPC is involved in sensory information integration and generates decision-related activity (see for review Romo & de Lafuente 2012), it is likely involved in motor recovery response to balance perturbation.

Based on the premise that balance control requires a minimum state of attention and of cognitive resources (Lajoie et al. 1993; Jacobs et al. 2008; Maki et McIlroy 2007; see for review Boisgontier et al. 2011), facilitating the detection of balance instability when standing on a biomimetic moving surface should decrease the attentional demand required for standing steadily. By using a dual task (DT) paradigm (*Experiment 2*) in which participants were involved in a cognitive task, while their supporting surface translated sideways, we expected smaller interference between the postural and cognitive tasks when participants stood on a biomimetic surface compared to other surfaces (e.g., smooth). This should result in a better performance in the cognitive task or a sharper postural reaction to the surface translation (i.e., large, short-duration postural reactions, Redfern et al., 2002).

Materials and Methods

EXPERIMENT 1

Participants and task

Fifteen participants (9 women) without any known neurological and motor disorders participated in the experiment (mean age 26 ± 3 years, mean weight 64 ± 10kg). All participants, except two, characterized themselves as right footed. All participants gave their written informed consent to take part in this study, which conformed to the ethical standards set out in the Declaration of Helsinki and which was approved by the CERSTAPS ethic committee.

Participants were requested to stand barefoot with their feet at a natural distance apart on different types of surfaces (see below), fixed in the middle of a movable force platform. They wore a safety harness attached to the structure top. We ensured that the feet position remained the same throughout the experimental conditions. As the morphology of foot (i.e., flat, hollow, standard) can have an impact on body stability (Klein et al., 2008), we verified that none of them had any foot morphological particularities. This was done by measuring the width of the forefoot (i.e., metatarsal band from the first to the 5th toe) and the isthmus width localized in the middle of the foot and connecting the forefoot with the rearfoot. A percentage ratio

((isthmus width)/ (forefoot width) x 100) allowed us to determine the hollow foot (<33%), standard foot (33% to 50%) and flat foot (>50%) (Klein et al., 2008). All participants showed standard feet, therefore none of them have been excluded from the analyses.

We used a set-up employed in previous studies for stimulating foot tactile afferents (e.g., Saradjian et al. 2019). A movable force platform is placed on two parallel rails and is held stationary by an electromagnet (Fig. 1A). A cable is attached to the platform and run laterally through a pulley system with a load fixed to its extremity. The platform translation is triggered by deactivating the electromagnet. The load is adapted to the weight of the participants, such that switching off the electromagnet translated the platform very slowly to the right of the participants, without endangering their balance. A triaxial accelerometer (MEMS, model 4630, Measurement Specialities, USA; 1000 Hz) was used to measure the platform acceleration (mean peak acceleration across participants of 41 ± 4 $cm.s^{-2}$).

At the start of a trial, the participants looked at fixation point positioned at eye level, 2m directly ahead. They were asked to close their eyes upon receiving the verbal information on the nature of the upcoming condition, and to remain still. This information indicated one of these two conditions: platform translation (37 trials) or platform steady (8 trials), which were pseudo-randomly distributed. The later set of trials reduces the possibility of adopting a stereotyped postural set linked to the forthcoming body translations. These trials were also used as baseline to analyse the EEG activities (see below). In all trials, the participants had to maintain an upright steady posture during 5 seconds (i.e., duration of trial recording). The platform translation occurred at any time between 1s and 2 s after providing the information about the platform (translation or steady) to avoid anticipating the instant of the translation onset. The trials without translation also lasted 5 s. A short break was frequently proposed to the participants during the experiment.

Surfaces

Participants were standing on three different surfaces that were glued on the platform: a biomimetic surface, a textured surface with no bioinspired features characteristics (i.e., grooved) and a smooth surface (the last two surfaces were used as controls). These surfaces were created with a 3D printer (Ultimaker 2+) using biopolymer thermoplastic (Polylactic acid, PLA). Three characteristics were selected to build the biomimetic surface: shape, spatial period, and depth of the ridges.

The biomimetic surface was textured with circular or oval shapes inspired from both the shape of the tactile receptors' fields that demonstrate a preferential skin strain axis and

orientation of this axis, which is not the same for all units (Kennedy & Inglis, 2002; Valbo et al., 1995), and the form of the dermatoglyphs, which exhibit three main circular forms (loops, whorls, and arcs, Cummins et Midlo 1926). We verified whether the radius of curvature of the circular shape complied with the participants' toe prints. To do so, we used the ink dabbing method to collect the toe prints of each participant on a white sheet of paper. Contrary to fingerprints, toe prints have their characteristic features in the lower end of the phalanges (Sarma, 2020). Then, the rolling of the prints was taken longitudinally from lower end to the upper end of the toe (i.e., opposite direction than when collecting fingerprints). For each participant, we measured, and then averaged, the radius of curvature of the 3 most visible ridges from 3 different toes. A t-test of means against a reference value indicated that the radius of curvature on the toes surface (4.3 ± 1.1 mm) did not differ significantly compared to the radius of the loops printed of the biomimetic surface (t_{13}= 1, p= 0.34).

The spatial period of the biomimetic surface complied with the period of the participants' toeprints ridges. This was confirmed by the result of the t-test of means against a reference value showing that the mean period of the biomimetic surface (0.9 mm) was not significantly different from the period of the toeprints ridges (0.87 ± 0.06 mm) (t_{13}= -1.66, p= 0.12). Note that the spatial period of the biomimetic surface also complied with the distance between the centre of adjacent receptive fields of the mechanoreceptors **(**from 0.9 to 3.8 mm; Johansson et Vallbo 1983).

Finally, the depth of the valley was computed from what we know from finger surface exploration and balance maintenance literature. The depth to properly perceive the stimulus on the finger skin is 0.1 mm with a 0.5 N of normal force (Camillieri et al., 2018; Peyre et al., 2017). When standing in a natural position, the minimum shear forces amplitude to detect support translation beneath the feet was on average 3.46 N (Mouchnino & Blouin, 2013). This lead to the suggestion that a 0.7 mm depth of the valley should enable to perceive the minimal shear force when bearing our body weight.

A smooth surface printed in PLA without any designed patterns was used as a control surface. To ensure that eventual differences between the SEP recorded in the biomimetic and smooth surface conditions could not simply be due to the mere presence of texture in the biomimetic surface, we also used a grooved surface as a second control surface. The texture of the grooved surface was composed of rectilinear ridges with a depth of 0.3 mm and a period of 7 mm.

The order of the 3 surface expositions were counterbalanced across participants. The participants were not informed prior to the experiment about the reason they stood on different

surfaces. When the participants were asked after the experiment whether they perceived that the surfaces had different textures, none of them reported having done so.

Recordings and analyses

Electroencephalography (EEG) activity was continuously recorded from 64 Ag/AgCl surface electrodes embedded in an elastic cap (BioSemi ActiveTwo system: BioSemi, Netherlands). Specific to the BioSemi system, "ground" electrodes were replaced by Common Mode Sense active and Driven Right Leg passive electrodes. The signals were pre-amplified at the electrode sites, post amplified with DC amplifiers, and digitized at a sampling rate of 1024 Hz (Actiview acquisition program). The signals of each electrode were referenced to the mean signal of all electrodes. Four Ag/AgCl electrodes placed near the canthus of each eye and under/over the left eye orbital allowed us to control for horizontal and vertical eyes' movements.

The continuous EEG signal was segmented into epochs synchronized relative to the onset of the platform translation, which was identified at the onset of the monotonic increase of the shear force. After artefact rejections based on visual inspection, 96 % of trials were included in the analyses. The signals were filtered off-line with a 50 Hz digital notch filter (24 dB/octave), when necessary, and with a 0.1–48 Hz band-pass digital filter (48 dB/octave) implemented in BrainVision Analyzer 2 software (Brain Products, Germany). For each participant, the SEPs were obtained by averaging all epochs of each surface for each participant. The average amplitude computed 50 ms prior to the platform translation served as baseline. Consistent with studies recording cortical potentials evoked by lower limb stimulation (Altenmüller et al., 1995; Saradjian et al., 2013), the SEPs were found to be maximal over the Cz electrode. Therefore, this electrode was used to assess the SEPs. We primarily based our analyses on the P_1N_1 wave evoked by the sensory stimulation induced by the platform translation. The amplitude of P_1N_1 was measured peak to peak, and its latency was assessed measuring the P_1 latency.

Cortical sources

Neural sources of the SEPs were estimated with the dynamical Statistical Parametric Mapping (dSPM, Dale et al., 2000) implemented in the Brainstorm software. A boundary element model (BEM) with three realistic layers (scalp, inner skull, and outer skull) was used to compute the forward model on the anatomical MRI brain template from the Montreal Neurological Institute (MNI Colin27). Using a realistic model has been shown to provide more

accurate solution than a simple three concentric spheres model (Sohrabpour et al .2015). We used of a high number of vertices (i.e., 15 002 vertices) to enhance the spatial resolution of the brain template. Such EEG source reconstruction has proved to be suited for investigating the activity of outer and inner cortical surfaces with 64 sensors (Chand & Dhamala, 2017; Ponz et al., 2014). Measuring and modelling the noise contaminating the data is beneficial to source estimation. Noise covariance matrices were computed using the 8 trials with platform steady condition, while the participants stood still. The current maps were averaged over the window from the start of the shear forces to N1 for each participant and surface condition. Then, using t-tests (Tadel et al., 2011), we compared the currents maps between the Biomimetic and Smooth conditions, and between the Biomimetic and Grooved conditions (significance threshold $p < 0.05$). We applied an FDR (False Discovery Rate) correction for multiple comparisons across regions (Benjamini & Hochberg, 1995).

The data were transformed into time-frequency domain using Morlet wavelet transforms. We used a 1Hz central frequency (full width at half maximum FWHM tc=3sec) because it offered a good compromise between temporal and spectral resolutions (Allen & MacKinnon, 2010). The power of theta (5-7 Hz), as an electrocortical indication of impending loss of balance was computed for each trial in the source space. The event-related synchronization/desynchronization (ERS/ERD) computations were performed in the PPC region of interest (ROI) encompassing the inferior and superior posterior parietal cortex based on the Destrieux cortical atlas (Destrieux et al., 2010). The power of theta cortical oscillations was computed for each trial in these ROIs from the left (589 vertices) and right (i.e., control ROI; 650 vertices) PPC and then averaged across trials for each surface and participant. We normalized the frequency powers by computing averaged theta ERS/ERD baseline -400 to -50ms. The theta power was computed over a -400ms period from the stimulation/translation onset so that our ERD/ERS analyses during the P1N1 SEP (i.e., 50ms to 100ms) was not impacted by edge effects.

Behavioural recordings and analyses

The ground reaction forces and moments were recorded with an AMTI force platform (60 × 120 cm, Advanced Mechanical Technology Inc., USA) at a sampling rate of 1000 Hz. The ground reaction shear forces were analysed along the mediolateral (M/L) axis, as they represent the earliest signature of cutaneous stimulation when the platform translation was present. The onset of the force, due to the platform translation, was considered to occur when its signal starts increasing monotonically.

As shown in Fig.1B for the translation condition, different consecutive phases are found:
i) the first phase shows a ramp of the platform acceleration (constant jerk) corresponding to a ramp in the traction force, due to the inertia of the platform plate, to which the force sensors are connected; this phase approximately lasts 197 ± 11ms leading to a platform displacement of about 2.93 ± 0.30 mm. Due to the inertia of the body, this displacement is accommodated mainly by the skin deformation. The peak amplitude of this force was measured with respect to its baseline value (i.e., prior to the translation onset);
ii) in a second phase, the force is transmitted to the foot by the skin, increasing the inertia of the mass in motion, leading to a larger inertia and thus to a decrease of the acceleration of the overall system; this is a crucial phase, where the contact between the skin and the surface is characterized by high superficial shearing, leading to transient variations of the local strain distribution ("*skin-surface contact transitions*"), which are directly affected by the topography of both the skin and the surface itself; moreover, local detachments and slipping can occur, leading to transient deformations and waves propagating in the skin, which are likely to activate the mechanoreceptors ("*contact stimuli*"); a similar phenomenon has been observed in literature, when considering the motion of a surface under a stationary fingertip, showing that the deformation of the skin increases until the frictional force (i.e., shear force) cannot anymore resist the sliding (i.e., stick/slip phenomenon, Rabinowicz 1956); within this phase, the shear forces result from a balance between inertia effects and contact accommodation, showing a peak followed by a low valley and then increase again; the jerk decreases and become negative in the following phase;
iii) Afterwards the shear forces continued to increase in the same direction until a second peak was reached before reversing the forces. This second increase can be considered as a postural reaction (Lhomond et al., 2021; Saradjian et al., 2019). The duration of the postural reaction was defined as the time elapsed between these peaks.
The amplitudes of both peaks of the shear forces were normalized to the body mass index (BMI) of each participant.

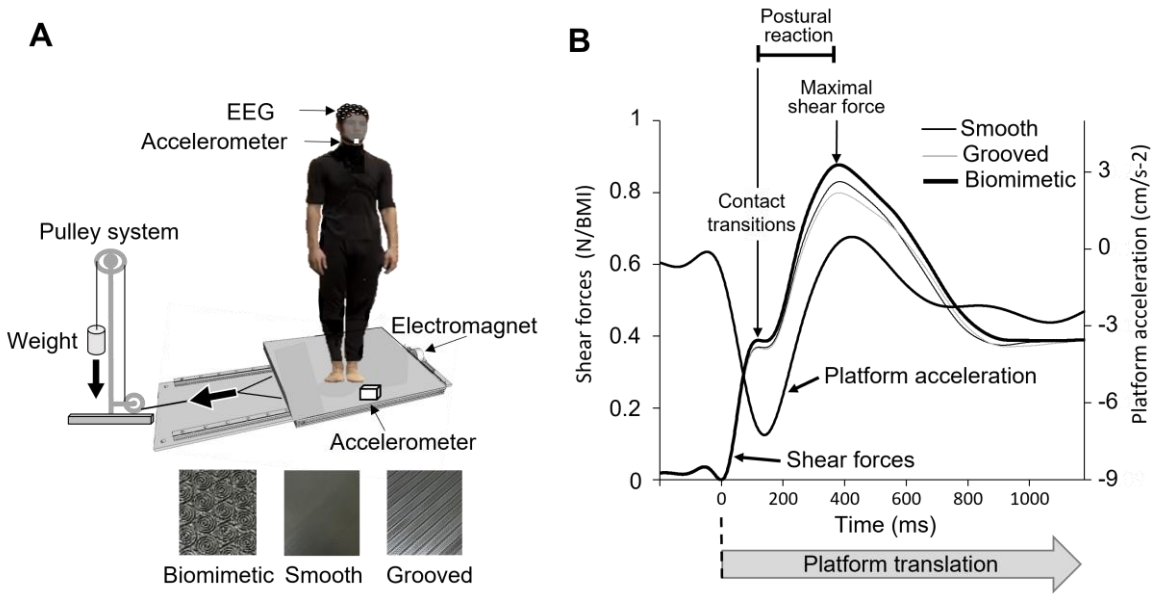


Figure 1. A. *Experimental set up. The participant stood on one of the three surfaces glued on the force platform which, on deactivation of the electromagnet, would undergo a translation to gravity loading. They wore a safety harness (not shown in the figure) attached to the structure top.* ***B.*** *Mean lateral forces and platform acceleration of the 15 participants. At the platform translation onset (broken line) two consecutive phases in lateral force were observed. The first peak force corresponds to the maximal extensibility of the skin under the feet until the frictional force (i.e., shear force) cannot anymore resist the sliding leading to transient variations of the local strain distribution ("skin-surface contact transitions"). Afterwards, a second force peak occurred and corresponds to a postural reaction.*

Head acceleration was measured with a triaxial accelerometer (model 4630, Measurement Specialities, USA; 1000 Hz) placed on the participants' chin. We measured head acceleration to evaluate the latency of the vestibular stimulation induced by the platform translation. The onset of the vestibular stimulation was defined at the first moment head acceleration exceeded 0.048 $m.s^{-2}$ (i.e., threshold for vestibular stimulation, (Gianna et al. 1996). We measured the lag between this head acceleration and the shear forces to determine if vestibular stimulation occurred after the mechanoreceptor's stimulation.

Bipolar surface electromyography (EMG, Bortec AMT-8 system, Bortec Bomedical, Canada) was used to record the activity of the long fibular muscle (FL) of both legs. Activation of the FL muscles is among other muscles responsible for controlling stance. They contribute to the eversion movement of the foot, and also in the maintenance of the arch of the foot to ensure optimal postural stability (Pietrosimone & Gribble, 2012; Jeon et al., 2021). EMG signals were pre-amplified at the skin site (×1000) sampled at 1000 Hz, band pass filtered from 20 to 250 Hz, and rectified. Two participants showed noisy EMG signals and were excluded from the EMG analyses. To quantify the muscle activity, we computed the integral of the EMG

activity (iEMG) over two intervals. The first corresponded to the "resting interval". It lasted 1 s and it ended at the onset of the platform translation. The second interval covered the time elapsed between the platform onset and the N1 component of the SEP. The duration of this second period was specific to each participant. In order to be able to compare muscle activities between the two intervals, we normalized, for each participant, the EMG activity of the resting interval to the duration of the second interval "N1 latency" (~180ms). EMG analysis was also performed by calculating the latencies of EMG changes relative to the platform translation. The mean and standard deviation of the muscle background activity were calculated for each participant and surface. The onsets of the EMG increased or decreased activities were defined by the times at which the EMG activity increased above or decreased below a threshold level set at twice the standard deviation of the mean background activity.

EXPERIMENT 2

Participants and task

The goal of *Experiment 2* was to test whether the attentional demand required for equilibrium maintenance is reduced when standing on the biomimetic surface, compared to a control surface. To further test the effect of standing on a surface which texture is inspired by the spatial characteristics of both mechanoreceptors and dermatoglyphs, with respect to standing on a non-biomimetic textured surface, the grooved surface was selected as the control surface in *Experiment 2*. While the smooth surface is used as standard control surface, a textured surface with different texture parameters, i.e. different from the ones of the dermatoglyphs and characterized by a main direction, allows for excluding a simple effect of the local strain variation due to a general texture. Comparing the biomimetic texture with a standard texture can then highlight the role played by a geometrical distribution of the texture mimicking the receptive features of the foot skin. Such a biomimetic geometry can give rise to local stress and strain distributions with a specific orientation pattern, which can favour the detection of the transient strain variations by the mechanoreceptor activation.

Twenty-one new participants (7 women) without any known neurological and motor disorders participated in the experiment (mean age 22 ± 2 years, mean weight 67 ± 10kg). All participants gave their written informed consent to take part in this study, which conformed with the ethical standards set out in the Declaration of Helsinki and which was approved by the CERSTAPS ethic committee.

The procedure was identical to that in *Experiment 1* with one exception that pertained to the dual task (DT) paradigm. We used a demanding cognitive task to increase the participants'

attentional load while their supporting surface was translated as in *Experiment 1*. Participants were asked to listen to a series of 10 different three-digit numbers (1Hz) that ended 60ms before the platform translation. The 10 numbers were spelled out at high speed (being completed in 10 s) by a computer voice. The series of numbers varied across trials but were the same for both surface conditions and participants. Participants were instructed to count silently the number of times that 7 was part of the three-digit numbers and to provide their response at an auditory tone signalled 3 s after the platform translation onset (i.e., after the data analysed intervals). The same procedure was used for the trials in the steady platform condition. We counterbalanced the presentation of the different conditions (i.e., biomimetic or grooved surfaces, with or without translation; single or dual task) across participants but prevented the possibility for the participant to have 2 successive conditions involving the dual task.

The participants' performance in the cognitive task was assessed by computing, in each surface condition, the averaged percentage of errors ((number of errors/10 numbers) x 100). An error was counted each time that the participant reported a wrong number of times that 7 was part of the spelled-out numbers.

Statistical analyses

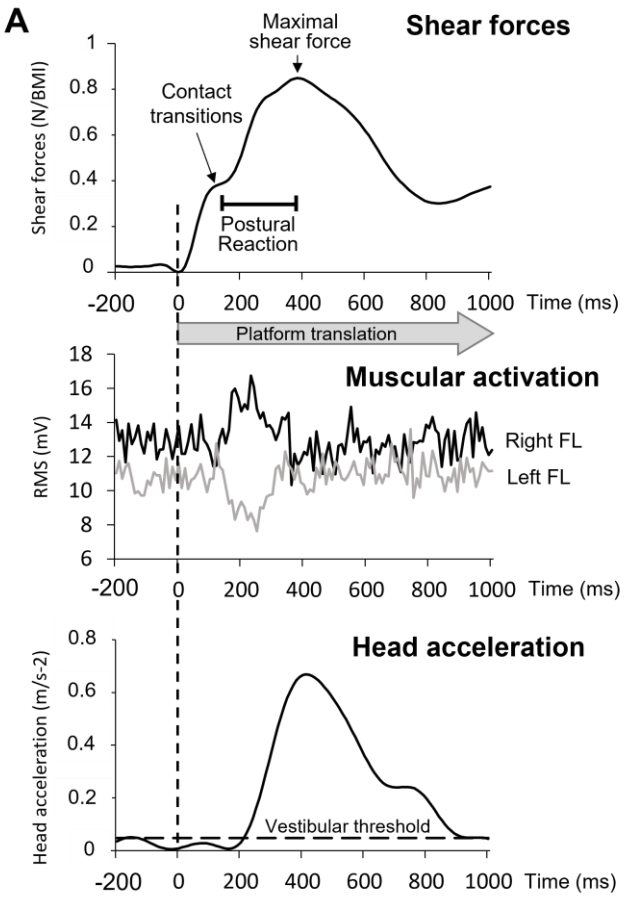
The behavioural and EEG data were submitted to separate analysis of variance (ANOVA) with repeated measurements. In *Experiment 1*, one-way ANOVAs were used for mean comparisons with the support surface (Smooth, Grooved, Biomimetic) as intra-participants factor. We computed statistical maps by contrasting the current maps (i.e., each vertice) obtained when standing on a biomimetic surface and control surfaces using t-tests (significance threshold $p < 0.05$). In *Experiment 2*, a 2x2 ANOVA was used for mean comparisons with the support surface (Grooved, Biomimetic) and task (single or dual task) as intra-subject factors. Significant effects (statistical threshold of $p \leq 0.05$) were further analysed using Newman-Keuls post-hoc tests. T-test were also used when specified.

Experiment 1 - Results

Augmented peripheral stimulation by the biomimetic design of the surface

As shown in Fig. 1B, the shear forces increased in the leftward direction at the onset of the rightward platform translation until a clear break down point was reached (see methods). It occurred before reaching the maximal value of the platform acceleration for all surfaces (-26 ± 11ms; paired t-test Ps <0.001). The peak of the platform acceleration did not show significant surface effect ($F_{2,28}$ = 2.09, p= 0.14). The lag of the peak acceleration relative to the shear force break down point confirmed that the first peak of the shear forces was not generated by the reaching of the maximum acceleration of the platform and the consequent change in the sign of the jerk, but rather by the contact transmission between the stretched skin and the platform. The results showed that latency of the break down point did not depend on the surface (overall mean of 117 ± 12ms; $F_{2,28}$ = 0.12, p= 0.89) whereas the amplitude did (Fig. 2B; $F_{2,28}$ = 13.84, p < 0.05). Post-hoc analysis showed that the amplitude was greater for the biomimetic (0.40 ± 0.05 N/BMI) than for the grooved and smooth surfaces (Ps < 0.05), which did not differ significantly (p = 0.20; overall mean of 0.38 ± 0.05 N/BMI). The EMG recordings (Fig 2A) showed that the activity of the right FL muscle started to increase 40 ± 20ms after the break down point and that the latencies were not significantly affected by the surface condition ($F_{2,24}$= 0.64; p = 0.54). The left FL activity decreased simultaneously with the right FL activation, when observed for some 10 out to 13 participants. The lag between the break down point and right FL muscle activity suggested that the early shear forces were passively evoked by platform translation, and therefore were mechanically rather than muscularly induced. This confirmed that the first peak in the shear forces corresponded to “skin-surface contact transitions” (see methods).

Besides observations that only the right FL (among the 2 recorded muscles) started to be activated after the “skin-surface contact transitions” (i.e., during the postural reaction) suggested that it was engaged in the breaking of balance perturbation. The postural reaction that followed the “skin-surface contact transitions” was not altered by the surface conditions either for the amplitude ($F_{2,28}$= 2.50; p = 0.10, mean = 0.53 ± 0.10 N/BMI) or the duration ($F_{2,28}$= 0.20; p= 0.82, mean = 296 ± 64ms). The head started moving (i.e., accelerate) during the postural reaction with a latency of 172 ± 38 ms relative to the platform translation (Fig. 2A). This lag, which likely resulted from the body mass inertia, was not significantly affected by the surface condition ($F_{2.28}$ = 1.48; p= 0.25).



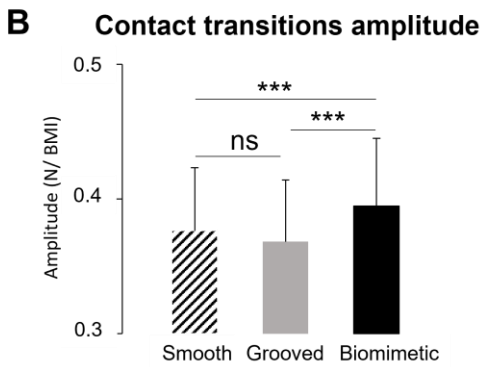


Figure 2. A. *Averaged shear forces (top panel), muscular activities (middle panel) and head accelerations (bottom panel) for all trials of one typical participant standing on the grooved surface. The time 0 (broken line) corresponds to the onset of the platform translation.* ***B.*** *Mean contact transitions amplitudes for all 15 participants computed on the three surfaces (smooth, grooved, biomimetic). Error bars represent standard deviation across participants; *** $p < 0.001$, ns = not significant.*

Cortical facilitation of sensory input when standing on a biomimetic surface

To determine whether the SEP (i.e., P_1N_1) originated from tactile and/or vestibular peripheral inputs, we compared the latencies of P_1 and N_1 to the vestibular stimulation onset. Paired t-tests showed that P_1 and N_1 latencies significantly preceded vestibular stimulation onset for all the surfaces (see Table 1) and that this time was not significantly affected by the surface condition ($F_{2,28}$= 1.75; p = 0.19). This indicated that the SEP was not evoked by vestibular inputs, but more likely by cutaneous inputs originated from the shear forces (i.e., skin strain) evoked by the platform translation.

Smooth		***Grooved***		***Biomimetic***	
Vestibular threshold					
211ms (±40)		225ms (±27)		207ms (±32)	
P1	**N1**	**P1**	**N1**	**P1**	**N1**
138ms (±11)	186ms (±15)	137ms (±13)	184ms (±18)	126ms (±16)	187ms (±13)
T test					
t = 7.09 ; p<0.001	t = 2.79 ; p = 0.01	t = 12.12; p<0.001	t = 5.50; p<0.001	t = 9.93; p<0.001	t = 2.68 ; p = 0.02

Table 1. *Mean latencies of all participants (n = 15) and inter participants standard deviation (SD) for the P1, N1 and the time when the head reached the vestibular threshold as a function of the surfaces on which participants were standing. The paired t test correspond to the comparison between the P1 or N1 and the vestibular threshold.*

Importantly, the latency of P_1 was shorter and the amplitude of the P_1N_1 was greater for the biomimetic surface than for the smooth and grooved surfaces (Fig. 3). The significant main effect of the surface condition (contact stress and strain distribution obtained by the biomimetic topography) was confirmed by the P_1 latency ($F_{2.28} = 6.65$, $p = 0.004$) and the P_1N_1 amplitude ($F_{2,28} = 3.55$, $p = 0.04$), which did not show difference between the two control surfaces either for P_1 latency ($p= 0.81$) or P_1N_1 amplitude ($p= 0.65$). There was no significant effect of surface on N1 latency ($F_{2.28}= 0.41$, $p= 0.67$).

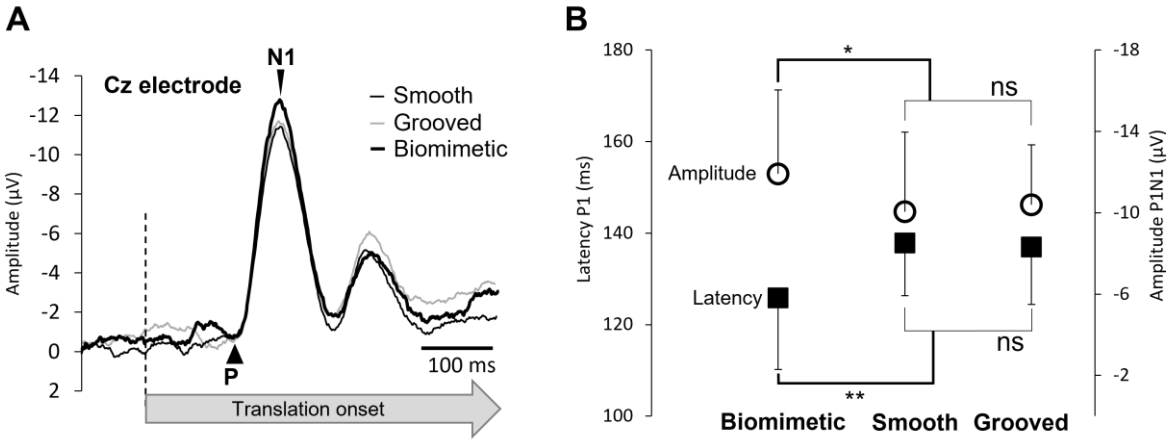


Figure 3. A. *Grand average (n=15) of the SEP recorded over Cz electrode for the 3 surfaces (biomimetic, smooth, grooved). The broken line indicates the moment of the stimulation (i.e., translation onset).* ***B****. Mean P1 latency and amplitude of the averaged P1N1 SEP for all participants on the three surfaces (biomimetic, smooth, grooved). Error bars represent standard deviation across participants, *p < 0.05; **p<0.01; ns = not significant.*

To verify if the SEP facilitation (i.e., shorter P_1 latency and greater P_1N_1 amplitude) observed with the biomimetic surface could be linked to a change in leg muscle activity, we compared the iEMG of the right and left FL during the N_1 latency interval. The ANOVA did not show a surface condition effect on the iEMG ($F_{2.24}= 0.57$; $p = 0.57$ and $F_{2.24}= 1.11$; $p = 0.34$, for the right and left FL, respectively). These results suggested that the changes in the SEP, observed when participants stood on the biomimetic surface, stemmed from an increased sensory input process than from an altered motor command (i.e., muscle activity).

Surface-specific source localization

The source analyses revealed significant greater activation in the left precuneus (mesial extent of Brodmann area 7, warm colour) for the biomimetic surface for both the

biomimetic/smooth (Fig. 4A) and biomimetic/grooved (Fig. 4B) contrasts. The same contrasts also showed significantly greater activity of the extrastriate body areas (EBA, BA19).

On the other hand, standing on the control surfaces resulted in greater activities of the left premotor (PM) and anterior cingular (ACC) cortices (see cold colors in Fig. 4A) for the smooth surface and greater activation of the right inferior PPC (BA39) for the grooved surface (Fig. 4B, cold colour).

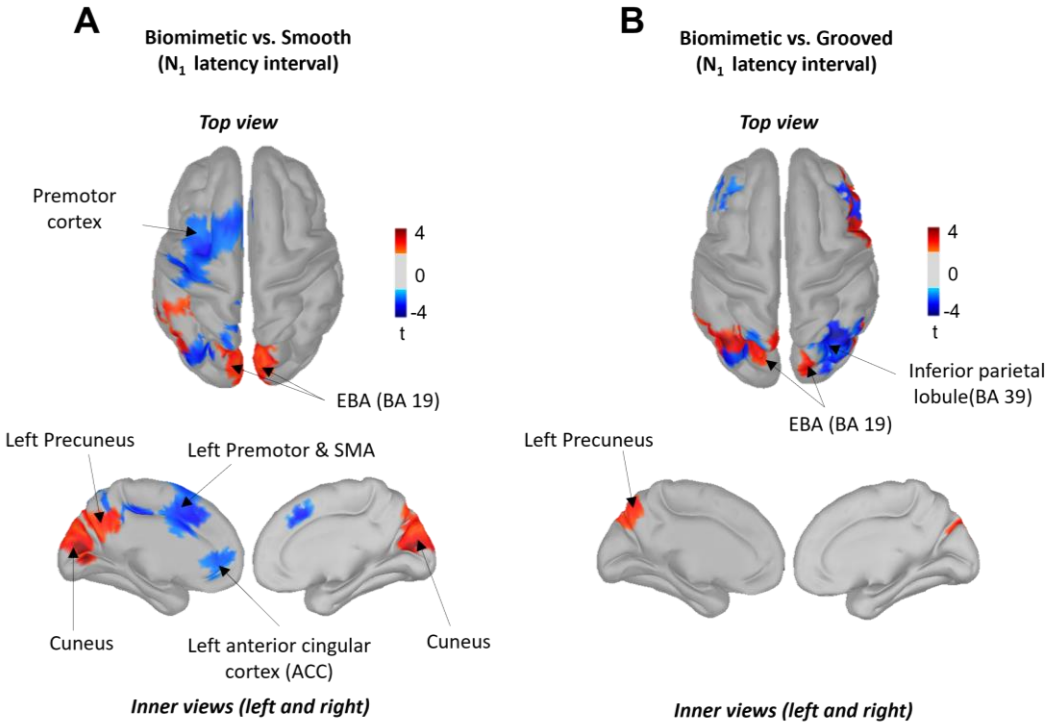


Figure 4. *Statistical source estimation maps for Biomimetic versus Smooth (A), Biomimetic versus Grooved (B) contrasts. Significant t-values ($p \leq 0.05$, n = 15) of the source localization were shown during the time window from 0 ms to N1 latency. Sources are projected on a cortical template (MNI's Colin 27). For each contrast, we display the top and the left and right inner cortical views.*

Modulation of theta (5-7 Hz) oscillations in the left PPC

The time-frequency analysis showed that theta power was modulated in relation to the surface on which the participants were standing. The ANOVA showed a significant effect of surface condition on theta power computed in the left PPC ($F_{2.28} = 3.99$; $p = 0.03$). Post-hoc analyses revealed that theta power was significantly smaller for the biomimetic than for smooth and grooved surfaces ($ps < 0.05$), with no significant difference between the two control surfaces ($p= 0.67$) (Fig. 5C). This effect was lateralized to the left hemisphere as it was not observed in the right PPC ($F_{2.28} = 1.32$; $p = 0.28$).

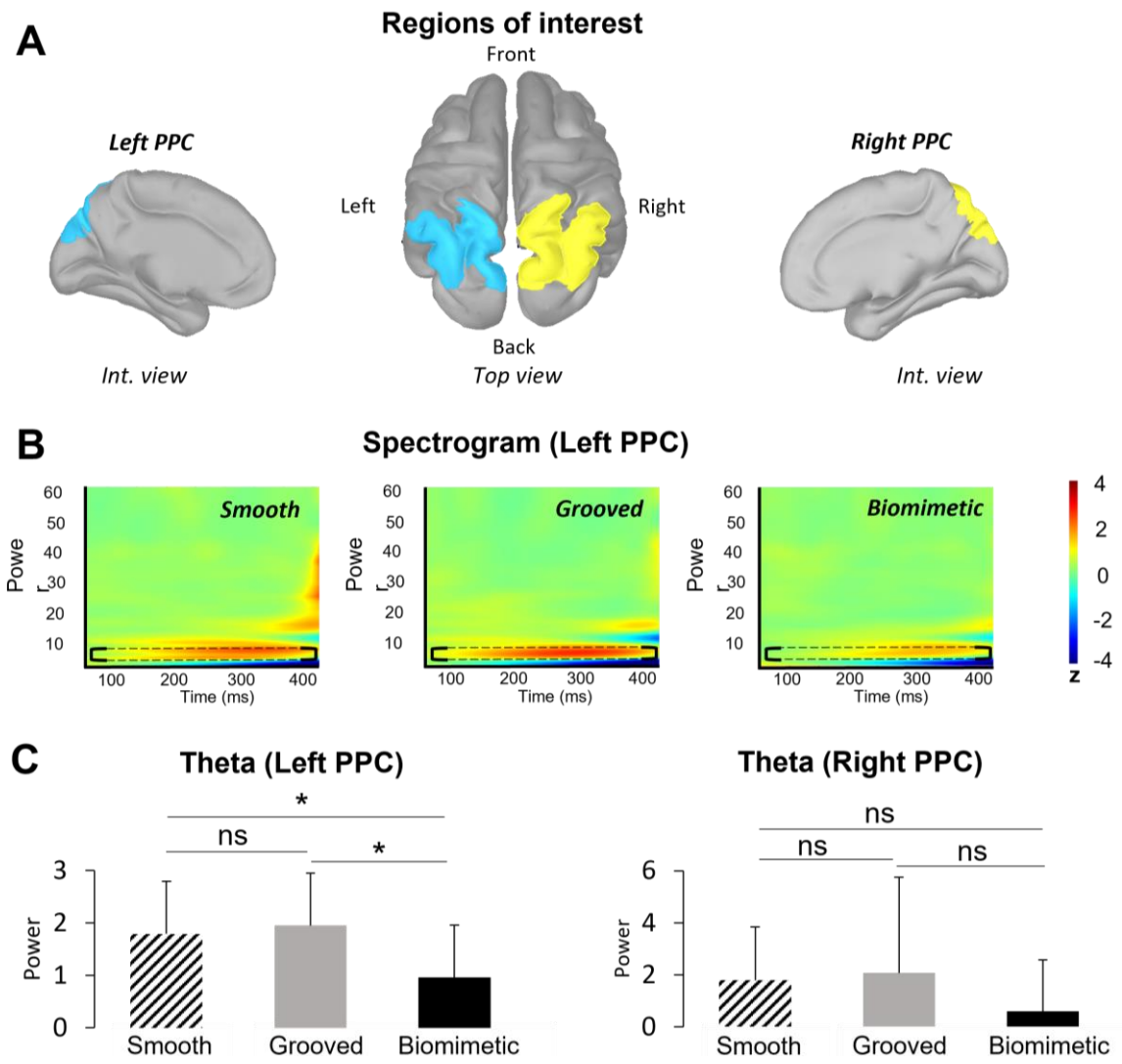


Figure 5. ***A***. *Localization of the regions of interest (ROIs) on the anatomical MRI Colin 27 brain template that was used to compute cortical activations. Note that similar ROIs were defined for the left and right Parietal Posterior Cortex (PPC).* ***B***. *Time-frequency power (ERS/ERD) of the signals by means of a complex Morlet's wavelet transform applied on the ROIs for each surface of each participant then averaged. Cooler colors indicate ERD and warmer colors, indicates ERS. Frequency bands from 1 to 90 Hz were provided to have an overview of the full spectral content of cortical neural oscillations. We showed the spectrum from 0 to 400 ms to focus on the analyzed time window of the ERS/ERD (thereby removing edge effects). The theta band has been circled in dotted line for each surface.* ***C***. *Mean of theta (5-7 Hz) frequency band computed during (0; 400 ms) time window in the left and right PPC for each surfaces (smooth, grooved, biomimetic). Error bars are standard error across participants, * $p < 0.05$, ns = not significant*

Discussion

Standing on a biomimetic surface speeds up and enhances the sensory transmission from foot to cortical areas

Complying with both dermatoglyphs and mechanoreceptors characteristics, the biomimetic surface in interaction with the feet evoked faster and greater cortical response to the platform translation (i.e., P_1N_1), with respect to both control surfaces (i.e., grooved and smooth). The greater amplitude of the SEP, when standing on the biomimetic surface, suggests augmented cutaneous afferent processes (see Desmedt et Robertson 1977; Hämäläinen et al. 1990; Salinas et al. 2000; Lin et al. 2003; Case et al. 2016; Lhomond et al. 2016). The increase P_1N_1 amplitude and the shortening of the evoked response latency (i.e., P_1) could probably be due to an accentuation of the deformation of the skin when interacting with the biomimetic surface. The enhanced skin transient deformations was witnessed by an increase amplitude of the peak force during the "skin-surface contact transitions" while no concomitant change of its duration was observed. This is in line with Tang et al.'s (2020) study showing that a greater deformation of the fingers' skin generates greater friction force, and stress that induces stronger tactile stimulation of the mechanoreceptors. Similarly, the interaction of the foot and the biomimetic surface increases the intensity of the skin mechanoreceptors stimulation, which in turn boosted the transmission of cutaneous signals to the primary somatosensory cortex (SI) where neurons respond to various tactile stimulations (e.g., Bensmaia et al. 2008; Weber et al. 2013). However, no difference between surfaces were observed in SI suggesting that the sensory facilitation observed with biomimetic surface may have involved direct thalamocortical projections to the PPC. The basis for this suggestion is 2-fold. First, neuroanatomical studies in the macaque have shown direct thalamocortical projections to the PPC (Pearson et al., 1978; Padberg et al., 2009; Impieri et al., 2018; Gamberini et al., 2020). Secondly, our results showed an increased activation of the mesial extent of the SPL (i.e., precuneus) for the biomimetic surface, with respect to both control surfaces, in line with functional interactions (e.g., somatomotor function) between the precuneus and the thalamus (Cunningham et al., 2017; Gamberini et al., 2020). In this light, the shared connectivity between the precuneus and the extrastriate body area (Zeharia et al., 2019), which showed an enhanced activity in the biomimetic surface condition, is consistent with the role of the EBA in enhancing the local spatial processing of body information on the direction of a stimuli out of view (Striem-Amit & Amedi, 2014; Urgesi et al., 2007), such as in the current study the skin stretch under the feet. This is also consistent with the role of EBA in hosting a multimodal representation of whole body or segment (Blanke et al. 2005; Arzy et al. 2006; Mouchnino et al. 2015).

The observed shorter latencies of the SEP could suggest some contribution of muscle-stretch receptors, as it is well-established that muscle spindle endings are extremely sensitive stretch receptors (see Starr et al. 1981; Cohen et al. 1985). However, the evoked potentials that arise from the stimulation of the lower limbs endings exhibit much shorter latencies (i.e., 20-65ms; Starr et al. 1981; Cohen et al. 1985) than those observed in the current study (126ms, for the biomimetic surface). Furthermore, the increased activity of the leg muscles induced by the translation of the biomimetic surface occurred ~160ms after the onset of the translation, i.e., after the P1 occurrence. This reduces the possibility for a significant role of muscle-stretch receptors in generating the SEP when participant stood on the translating surface, irrespectively of the type of supporting surface. Neither is vestibular input a likely candidate for evoking the cortical response, as P1 and N1 had shorter latencies than the latency with which the head reached the acceleration threshold for activating vestibular receptors (i.e., 207ms, for the biomimetic surface).

Decreased balance task difficulty when standing on the biomimetic surface

Finally, the results of theta oscillations analyses were consistent with the likely role of the left PPC (Hülsdünker et al., 2015; Mierau et al., 2017) in attentional processes. Our participants showed a significant decreased of theta oscillations power in the left PPC when they stood on the biomimetic surface compared to the control surfaces (i.e., grooved and smooth). Since theta oscillations are considered as neural correlate of a need for attentional demand in challenging balance tasks (Sipp et al. 2013; Hülsdünker et al. 2015; Gebel et al. 2020), the significant decrease in theta-band activity on the biomimetic surface may reflect a decrease in the attentional demand and a down modulation in the difficulty of the task (Vuillerme & Nafati, 2007). Alternatively, the increased theta power, observed when standing on both control surfaces, may witness the increase attentional and cognitive demands. This is consistent with greater activities observed within the pre-motor cortex (e.g., SMA) and ACC of the left hemisphere observed when the tactile salience of the surface decreases, as when standing on a smooth surface (as compared to either the biomimetic or grooved surfaces). Previous studies have suggested that the SMA plays an important role in the control of demanding balance tasks (Taubert et al., 2010, 2011). This was notably evidenced by the significant structural and functional adaptation of the SMA activity among other areas after balance training (Taubert et al., 2011). Therefore, the enhanced activity of the SMA, found when individuals stood on the smooth surface, may suggest that the standing task was more demanding with this surface than with textured surfaces (biomimetic or grooved). The increased

activity observed in the ACC would also be consistent with this suggestion as the role of this cortical region is well-recognized when individuals are uncertain about fulfilling the required task appropriately (e.g., Gemba et al. 1986) or in error-recognition (Holroyd et al., 1998; see for review Holroyd & Coles, 2002). These interpretations are also supported by the proposed function of the ACC in the regulation of attention and cognitive control (Botvinick et al., 2001; Bryden et al., 2011; Petersen & Posner, 2012). Enhancing the need for attention when standing on a smooth surface could be a mean for withholding potentially erroneous responses in conditions with impoverished tactile cues on platform translation until other sensory modalities (e.g., vestibular, visual) can resolve the ambiguity of support displacement. In addition to the increased theta oscillations power for the control grooved surface, the source analyses revealed an increased activation of the right PPC. This findings are consistent with the crucial role of this cortical area in the processing of somaesthetic gravitational information for postural control, as shown in neglect patients after right hemispheric strokes (Pérennou, 2006).

Overall, our results point to the interpretation that using a biomimetic surface reduces the difficulty of the balance task. In *Experiment 2*, we tested the hypothesis that standing on such a surface benefits postural control when the balance task is challenged by increasing the attentional load (Stelmach et al. 1990; Chen et al. 1996; Shumway-Cook et Woollacott 2000). Indeed, because postural control is known to requires attention (Lajoie et al., 1993), therefore the postural perturbation observed when performing a simultaneous cognitive task would be due to the sharing of limited attentional resources (see for review Woollacott et Shumway-Cook 2002).

Experiment 2 - Results

Cognitive task performance

To verify whether the participants' performance in the cognitive task differed when standing on the moving biomimetic and the grooved surfaces, we analysed the averaged percentage of errors reporting the number of times that 7 was part of the series of 3-digit numbers spelled out with high speed. A paired t-test did not reveal significant difference in the percentage of errors between the biomimetic and the grooved surfaces (t_{20}= -0.20; p = 0.85; 24 ± 11.5%). As shown in Figure 6A, 2 out 21 participants exhibited values three times above the standard deviation of the mean (i.e., 66% and 59% of errors). These large errors suggest that

the task was too difficult for these participants or that they did not allocate enough attentional resources to the cognitive task. These participants were excluded from the behavioural analysis.

Furthermore, the activity observed over the anterior prefrontal cortex and the orbito-frontal cortex during the last part of the counting (i.e, over a 2000 ms interval before the platform translation) were greater in the dual task than in the single task (Fig. 6B). This confirmed the participants' engagement in the cognitive task (McGuire & Botvinick, 2010; Wallis, 2007). Note that no such activities of the frontal lobe were observed in the 2 participants that were discarded from the analyses, due to their high error rate.

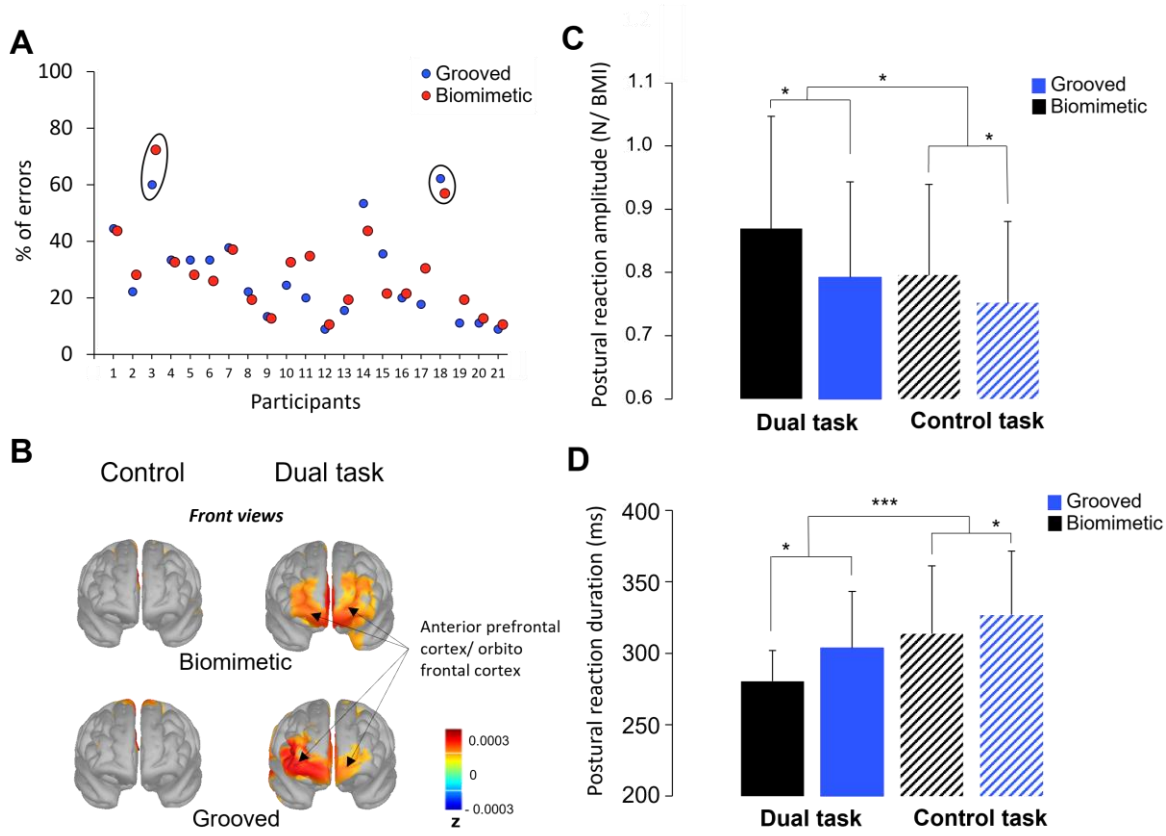


Figure 6. ***A****. Percentage of errors for the cognitive task of each participant on both surfaces (grooved, biomimetic).* ***B****. Source localization during the time window from -2000 to 0 ms latency interval on both surfaces (grooved, biomimetic) during solely the motor task (i.e., control) and the dual task. We display the front view of the sources are projected on a cortical template (MNI's Colin 27).* ***C****. Mean postural reaction amplitude normalized by the BMI for all participants computed on both surfaces (grooved, biomimetic) during solely the motor task (i.e., control) and the dual task. Error bars represent standard deviation across participants; * p <0.05)* ***D.*** *Mean postural reaction latency for all participants (n = 21) computed on both surfaces (grooved, biomimetic) during solely the motor task (i.e., control) and the dual task. Error bars represent standard deviation across participants; *** p < 0.001).*

Postural reaction in response to surface translation

The ANOVA indicated that postural reaction was of greater magnitude when performing the dual task (combined cognitive and motor tasks) than the single motor task ($F_{1,18}$= 4.78; p=0.04), and when standing on the biomimetic as compared to the grooved surface ($F_{1,18}$= 5.92, p=0.03). No significant interaction was observed between Task and Surface ($F_{1,18}$= 0.76; p=0.39). The ANOVA also revealed that the duration of the postural reaction was shorter when performing a dual task ($F_{1,18}$= 21.183; $p < 0.05$) and when standing on the biomimetic surface ($F_{1,18}$= 6.95; p = 0.02). The interaction Task x Surface was not significant ($F_{1,18}$= 0.43; p=0.51).

Although the ANOVAs, performed on the variables related to the postural reaction, did not reveal significant Task x Surface interactions, the inspection of the results shown in Fig. 6 suggests that the most efficient postural reaction was found when participants stood on the biomimetic surface in the dual-task condition (i.e., greater amplitude (Fig. 6C) and smaller duration (Fig. 6D) of the postural reaction). In support with this assumption and using planned contrasts post-hoc test, the results revealed that the postural reaction had significantly greater amplitude (F = 10.51; $p < 0.005$) and smaller duration (F = 37.70; $p < 0.001$) when standing on a biomimetic surface, rather than in the 3 other conditions.

Discussion

The intriguing result of *Experiment 2* is that the postural reaction observed during the platform translation had shorter duration and greater magnitude in the dual task than in the single task, irrespectively of the standing surfaces. These behavioural features comply with the spatiotemporal characteristics of an efficient postural reaction (Ikai et al. 2003; Horak et al. 1997). They were observed to a greater extent when the participants stood on the biomimetic surface. Therefore, the participants' engagement in the cognitive task did not have a deleterious consequence on the postural control as often reported in previous studies (e.g., Shumway-Cook et al. 1997; Kerr et al. 1985; Rankin et al. 2000; Melzer et al. 2001). The greatest efficiency of the postural reaction observed in participants standing on the biomimetic surface could stem from a greater capacity to shift the attentional focus from the primary motor task to the secondary cognitive task enabled by this surface. The benefit of this external focus is known to engage less conscious attentional processes (Vuillerme et Nafati 2007; see for review Wulf et Prinz 2001) than an internal focus of attention (Sherwood et al. 2020). For example, when the attention of participants was directed to the way in which their feet should exerted forces on the platform (i.e., internal focus), the performance decreased as compared to the situation where

the participants' attention was driven away from their own movements to the wheels of the platform, which were located directly under the feet (external focus, (Wulf et al. 1998). These results, with regards to the absence of difference in the postural reaction between surfaces observed in *Experiment 1*, suggest that some advantage of standing on a biomimetic surface, in order to safeguard stability, can solely be expressed when performing a dual task. It is possible that the equilibrium demands in response to support translation decreased when standing on a biomimetic surface, as suggested the observed decrease of theta power in *Experiment 1*. A low-level sensorimotor loop, which supports a speedy performance, may be involved (i.e., less permeable to cognitive load). As mentioned in conclusion 1, a thalamocortical projection to the left pre-cuneus (Cunningham et al., 2017; Gamberini et al., 2020) may have facilitated the neural responses where all parietal fields have interconnections with motor cortex, premotor cortex or both (see for review Krubitzer et Disbrow 2008). These thalamocortical connections areas could constitute the neural underpinning of the efficient spatiotemporal pattern of the postural reaction when standing on the biomimetic surface.

Conclusion

The discussed results add to the understanding of how a standing surface, when inspired by the living, influences the perception of the world around us. Furthermore, it has been observed as brain activity differs in a number of areas, acknowledging an efficient sensorimotor control when standing on a biomimetic surface. Understanding how attentional demand, during this challenging balance task, affects the brain information processing from the senses could provide new insights into peripheral/central interaction. This is paramount, as situations in everyday life often involve cognitive-motor dual tasks, e.g., answering the cell phone while walking, or singing while showering.

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References

Allen, D. P., & MacKinnon, C. D. (2010). Time-frequency analysis of movement-related spectral power in EEG during repetitive movements : A comparison of methods. *Journal of Neuroscience Methods*, *186*(1), 107-115. https://doi.org/10.1016/j.jneumeth.2009.10.022

Altenmüller, E., Berger, W., Prokop, T., Trippel, M., & Dietz, V. (1995). Modulation of sural nerve somatosensory evoked potentials during stance and different phases of the step-cycle. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *96*(6), 516-525. https://doi.org/10.1016/0013-4694(95)00093-E

Arzy, S., Thut, G., Mohr, C., Michel, C. M., & Blanke, O. (2006). Neural Basis of Embodiment : Distinct Contributions of Temporoparietal Junction and Extrastriate Body Area. *Journal of Neuroscience*, *26*(31), 8074-8081. https://doi.org/10.1523/JNEUROSCI.0745-06.2006

Basdogan, C., Giraud, F., Levesque, V., & Choi, S. (2020). A Review of Surface Haptics : Enabling Tactile Effects on Touch Surfaces. *IEEE Transactions on Haptics*, *13*(3), 450-470. https://doi.org/10.1109/TOH.2020.2990712

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate : A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289-300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bensmaia, S. J., Denchev, P. V., Dammann, F. J., Craig, J. C., & Hsiao, S. S. (2008). The Representation of Stimulus Orientation in the Early Stages of Somatosensory Processing. *The Journal of Neuroscience*, *28*(3), 776-786. https://doi.org/10.1523/JNEUROSCI.4162-07.2008

Blanke, O., Mohr, C., Michel, C. M., Pascual-Leone, A., Brugger, P., Seeck, M., Landis, T., & Thut, G. (2005). Linking Out-of-Body Experience and Self Processing to Mental Own-Body Imagery at the Temporoparietal Junction. *Journal of Neuroscience*, *25*(3), 550-557. https://doi.org/10.1523/JNEUROSCI.2612-04.2005

Boisgontier, M., Mignardot, J.-B., Nougier, V., Olivier, I., & Palluel, E. (2011). Le coût attentionnel associé aux fonctions exécutives impliquées dans le contrôle postural. *Science & Motricité*, *74*, 53-64. https://doi.org/10.1051/sm/2011106

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624-652. https://doi.org/10.1037/0033-295x.108.3.624

Bryden, D. W., Johnson, E. E., Tobia, S. C., Kashtelyan, V., & Roesch, M. R. (2011). Attention for learning signals in anterior cingulate cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *31*(50), 18266-18274. https://doi.org/10.1523/JNEUROSCI.4715-11.2011

Camillieri, B., Bueno, M.-A., Juan, B., Lemaire-Semail, B., Mouchnino, L., & Fabre, M. (2018). From finger friction and induced vibrations to brain activation : Tactile comparison between real and virtual textile fabrics. *Tribology International*, *126*, 283-296. https://doi.org/10.1016/j.triboint.2018.05.031

Carpenter, M. G., Murnaghan, C. D., & Inglis, J. T. (2010). Shifting the balance : Evidence of an exploratory role for postural sway. *Neuroscience*, *171*(1), 196-204. https://doi.org/10.1016/j.neuroscience.2010.08.030

Case, L., Laubacher, C. M., Olausson, H., Wang, B., Spagnolo, P. A., & Bushnell, C. M. (2016). Encoding of Touch Intensity But Not Pleasantness in Human Primary Somatosensory Cortex. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *36*(21), 5850-5860. https://doi.org/10.1523/jneurosci.1130-15.2016

Chand, G. B., & Dhamala, M. (2017). Interactions between the anterior cingulate-insula network and the fronto-parietal network during perceptual decision-making. *NeuroImage*, *152*, 381-389. https://doi.org/10.1016/j.neuroimage.2017.03.014

Chen, H.-C., Schultz, A. B., Ashton-Miller, J. A., Giordani, B., Alexander, N. B., & Guire, K. E. (1996). Stepping Over Obstacles : Dividing Attention Impairs Performance of Old More Than Young Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *51A*(3), M116-M122. https://doi.org/10.1093/gerona/51A.3.M116

Cohen, L. G., Starr, A., & Pratt, H. (1985). Cerebral somatosensory potentials evoked by muscle stretch, cutaneous taps and electrical stimulation of peripheral nerves in the lower limbs in man. *Brain*, *108*(1), 103-121. https://doi.org/10.1093/brain/108.1.103

Cornuault, P.-H., Carpentier, L., Bueno, M.-A., Cote, J.-M., & Monteil, G. (2015). Influence of physico-chemical, mechanical and morphological fingerpad properties on the frictional distinction of sticky/slippery surfaces. *Journal of The Royal Society Interface*, *12*(110), 20150495. https://doi.org/10.1098/rsif.2015.0495

Cummins, H., & Midlo, C. (1926). Palmar and plantar epidermal ridge configurations (dermatoglyphics) in European-Americans. *American Journal of Physical Anthropology*, *9*(4), 471-502. https://doi.org/10.1002/ajpa.1330090422

Cunningham, S. I., Tomasi, D., & Volkow, N. D. (2017). *Structural and functional connectivity of the precuneus and thalamus to the default mode network*. https://doi.org/10.1002/hbm.23429

Dale, A. M., Liu, A. K., Fischl, B. R., Buckner, R. L., Belliveau, J. W., Lewine, J. D., & Halgren, E. (2000). Dynamic Statistical Parametric Mapping : Combining fMRI and MEG for High-Resolution Imaging of Cortical Activity. *Neuron*, *26*(1), 55-67. https://doi.org/10.1016/S0896-6273(00)81138-1

de Lafuente, V., & Romo, R. (2006). Neural correlate of subjective sensory experience gradually builds up across cortical areas. *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*. https://doi.org/10.1073/pnas.0605826103

Desmedt, J. E., & Robertson, D. (1977). *Differential enhancement of early and late components of the cerebral somatosensory evoked potentials during forced-paced cognitive tasks in man*. 761-782. https://doi.org/10.1113/jphysiol.1977.sp012025

Destrieux, C., Fischl, B., Dale, A., & Halgren, E. (2010). Automatic parcellation of human cortical gyri and sulci using standard anatomical nomenclature. *NeuroImage*, *53*(1), 1-15. https://doi.org/10.1016/j.neuroimage.2010.06.010

Fearing, R. S., & Hollerbach, J. M. (1985). Basic Solid Mechanics for Tactile Sensing. *The International Journal of Robotics Research*, *4*(3), 40-54. https://doi.org/10.1109/ROBOT.1984.1087171

Gamberini, M., Passarelli, L., Impieri, D., Worthy, K. H., Burman, K. J., Fattori, P., Galletti, C., Rosa, M. G. P., & Bakola, S. (2020). Thalamic afferents emphasize the different functions of macaque precuneate areas. *Brain Structure & Function*, *225*(2), 853-870. https://doi.org/10.1007/s00429-020-02045-2

Gebel, A., Lehmann, T., & Granacher, U. (2020). Balance task difficulty affects postural sway and cortical activity in healthy adolescents. *Experimental Brain Research*, *238*(5), 1323-1333. https://doi.org/10.1007/s00221-020-05810-1

Gemba, H., Sasaki, K., & Brooks, V. B. (1986). « Error » potentials in limbic cortex (anterior cingulate area 24) of monkeys during motor learning. *Neuroscience Letters*, *70*(2), 223-227. https://doi.org/10.1016/0304-3940(86)90467-2

Gianna, C., Heimbrand, S., & Gresty, M. (1996). Thresholds for detection of motion direction during passive lateral whole-body acceleration in normal subjects and patients with bilateral loss of labyrinthine function. *Brain Research Bulletin*, *40*(5-6), 443-447. https://doi.org/10.1016/0361-9230(96)00140-2

Hämäläinen, H., Kekoni, J., Sams, M., Reinikainen, K., & Näätänen, R. (1990). Human somatosensory evoked potentials to mechanical pulses and vibration : Contributions of SI and SII somatosensory cortices to P50 and P100 components. *Electroencephalography and Clinical Neurophysiology*, *75*(1), 13-21. https://doi.org/10.1016/0013-4694(90)90148-D

Hollins, M., & Risner, S. R. (2000). Evidence for the duplex theory of tactile texture perception. *Perception & Psychophysics*, *62*(4), 695-705. https://doi.org/10.3758/bf03206916

Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing : Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*(4), 679-709. https://doi.org/10.1037/0033-295X.109.4.679

Holroyd, C. B., Dien, J., & Coles, M. G. H. (1998). Error-related scalp potentials elicited by hand and foot movements : Evidence for an output-independent error-processing system in humans. *Neuroscience Letters*, *242*(2), 65-68. https://doi.org/10.1016/s0304-3940(98)00035-4

Horak, F. B., Henry, S. M., & Shumway-Cook, A. (1997). Postural Perturbations : New Insights for Treatment of Balance Disorders. *Physical Therapy*, *77*(5), 517-533. https://doi.org/10.1093/ptj/77.5.517

Hülsdünker, T., Mierau, A., Neeb, C., Kleinöder, H., & Strüder, H. K. (2015). Cortical processes associated with continuous balance control as revealed by EEG spectral power. *Neuroscience Letters*, *592*, 5. https://doi.org/10.1016/j.neulet.2015.02.049

Ikai, T., Kamikubo, T., Takehara, I., Nishi, M., & Miyano, S. (2003). Dynamic Postural Control in Patients with Hemiparesis: *American Journal of Physical Medicine & Rehabilitation*, *82*(6), 463-469. https://doi.org/10.1097/01.PHM.0000069192.32183.A7

Impieri, D., Gamberini, M., Passarelli, L., Rosa, M. G. P., & Galletti, C. (2018). Thalamo-cortical projections to the macaque superior parietal lobule areas PEc and PE. *Journal of Comparative Neurology*, *526*(6), 1041-1056. https://doi.org/10.1002/cne.24389

Jacobs, J. V., Fujiwara, K., Tomita, H., Furune, N., Kunita, K., & Horak, F. B. (2008). Changes in the activity of the cerebral cortex relate to postural response modification

when warned of a perturbation. *Clinical Neurophysiology*, *119*(6), 1431-1442. https://doi.org/10.1016/j.clinph.2008.02.015

Jeon, W., Griffin, L., & Hsiao, H.-Y. (2021). Effects of initial foot position on postural responses to lateral standing surface perturbations in younger and older adults. *Gait & Posture*, *90*, 449-456. https://doi.org/10.1016/j.gaitpost.2021.09.193

Johansson, R. S., & Vallbo, Å. B. (1983). Tactile sensory coding in the glabrous skin of the human hand. *Trends in Neurosciences*, *6*, 27-32. https://doi.org/10.1016/0166-2236(83)90011-5

Kennedy, P. M., & Inglis, J. T. (2002). Distribution and behaviour of glabrous cutaneous receptors in the human foot sole. *The Journal of Physiology*, *538*(3), 995-1002. https://doi.org/10.1113/jphysiol.2001.013087

Kerr, B., Condon, S., & McDonald, L. (1985). Cognitive Spatial Processing and the Regulation of Posture. *Journal of Experimental Psychology; Human Perception and Performance*, *Vol. 11*(No. 5), 617-622. https://doi.org/10.1037//0096-1523.11.5.617

Klein, P., Sommerfeld, P., & Meddeb, G. (2008). *Biomécanique des membres inférieures* (Elsevier Masson).

Krubitzer, L., & Disbrow, E. (2008). *The Evolution of Parietal Areas Involved in Hand Use in Primates*. 33.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, *97*(1). https://doi.org/10.1007/BF00228824

Latash, M. L., Ferreira, S. S., Wieczorek, S. A., & Duarte, M. (2003). Movement sway : Changes in postural sway during voluntary shifts of the center of pressure. *Experimental Brain Research*, *150*(3), 314-324. https://doi.org/10.1007/s00221-003-1419-3

Lederman, S. J., & Klatzky, R. L. (2009). Haptic perception : A tutorial. *Attention, Perception & Psychophysics*, *71*(7), 1439-1459. https://doi.org/10.3758/APP.71.7.1439

Lhomond, O., Juan, B., Fornerone, T., Cossin, M., Paleressompoulle, D., Prince, F., & Mouchnino, L. (2021). Learned Overweight Internal Model Can Be Activated to Maintain Equilibrium When Tactile Cues Are Uncertain : Evidence From Cortical and Behavioral Approaches. *Frontiers in Human Neuroscience*. https://doi.org/10.3389/FNHUM.2021.635611

Lhomond, O., Teasdale, N., Simoneau, M., & Mouchnino, L. (2016). Neural Consequences of Increasing Body Weight : Evidence from Somatosensory Evoked Potentials and the

Frequency-Specificity of Brain Oscillations. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00318

Lin, Y.-Y., Shih, Y.-H., Chen, J.-T., Hsieh, J.-C., Yeh, T.-C., Liao, K.-K., Kao, C.-D., Lin, K.-P., Wu, Z.-A., & Ho, L.-T. (2003). Differential effects of stimulus intensity on peripheral and neuromagnetic cortical responses to median nerve stimulation. *NeuroImage*, *20*(2), 909-917. https://doi.org/10.1016/S1053-8119(03)00387-2

Maki, B. E., & McIlroy, W. E. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal of Neural Transmission*, *114*(10), 1279-1296. https://doi.org/10.1007/s00702-007-0764-y

Massimiani, V., Benjamin, W., Eric, C., Pierre-Henri, C., Jenny, F., & Francesco, M. (2020). The role of mechanical stimuli on hedonistic and topographical discrimination of textures. *Tribology International*, *143*, 9. https://doi.org/10.1016/j.triboint.2019.106082

Mauguière, F., Merlet, I., Forss, N., Vanni, S., Jousmäki, V., Adeleine, P., & Hari, R. (1997). Activation of a distributed somatosensory cortical network in the human brain : A dipole modelling study of magnetic fields evoked by median nerve stimulation. Part II: effects of stimulus rate, attention and stimulus detection. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *104*(4), 290-295. https://doi.org/10.1016/S0013-4694(97)00018-7

McGuire, J. T., & Botvinick, M. M. (2010). Prefrontal cortex, cognitive control, and the registration of decision costs. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(17), 7922-7926. https://doi.org/10.1073/pnas.0910662107

Melzer, I., Benjuya, N., & Kaplanski, J. (2001). Age-Related Changes of Postural Control : Effect of Cognitive Tasks. *Gerontology*, *47*(4), 189-194. https://doi.org/10.1159/000052797

Mierau, A., Pester, B., Hülsdünker, T., Schiecke, K., Strüder, H. K., & Witte, H. (2017). Cortical Correlates of Human Balance Control. *Brain Topogr*, 434-446. https://doi.org/10.1007/s10548-017-0567-x

Mochizuki, L., Duarte, M., Amadio, A. C., Zatsiorsky, V. M., & Latash, M. L. (2006). Changes in Postural Sway and Its Fractions in Conditions of Postural Instability. *Journal of Applied Biomechanics*, *22*(1), 51-60. https://doi.org/10.1123/jab.22.1.51

Morasso, P. G., & Schieppati, M. (1999). Can Muscle Stiffness Alone Stabilize Upright Standing? *Journal of Neurophysiology*, *82*(3), 1622-1626. https://doi.org/10.1152/jn.1999.82.3.1622

Mouchnino, L., & Blouin, J. (2013). When Standing on a Moving Support, Cutaneous Inputs Provide Sufficient Information to Plan the Anticipatory Postural Adjustments for Gait Initiation. *PLoS ONE*, *8*(2), e55081. https://doi.org/10.1371/journal.pone.0055081

Mouchnino, L., Fontan, A., Tandonnet, C., Perrier, J., Saradjian, A. H., Blouin, J., & Simoneau, M. (2015). Facilitation of cutaneous inputs during the planning phase of gait initiation. *Journal of Neurophysiology*, *114*(1), 301-308. https://doi.org/10.1152/jn.00668.2014

Murnaghan, C. D., Horslen, B. C., Inglis, J. T., & Carpenter, M. G. (2011). Exploratory behavior during stance persists with visual feedback. *Neuroscience*, *195*, 54-59. https://doi.org/10.1016/j.neuroscience.2011.08.020

Padberg, J., Cerkevich, C., Engle, J., Rajan, A. T., Recanzone, G., Kaas, J., & Krubitzer, L. (2009). Thalamocortical Connections of Parietal Somatosensory Cortical Fields in Macaque Monkeys are Highly Divergent and Convergent. *Cerebral Cortex*, *19*(9), 2038-2064. https://doi.org/10.1093/cercor/bhn229

Pearson, R. C. A., Brodal, P., & Powell, T. P. S. (1978). The projection of the thalamus upon the parietal lobe in the monkey. *Brain Research*, 143-148. https://doi.org/10.1016/0006-8993(78)90440-7

Pérennou, D. (2006). Postural disorders and spatial neglect in stroke patients : A strong association. *Restorative Neurology and Neuroscience*, *24*(4-6), 319-334.

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain : 20 years after. *Annual Review of Neuroscience*, *35*, 73-89. https://doi.org/10.1146/annurev-neuro-062111-150525

Peyre, K., Tourlonias, M., Bueno, M.-A., & Rossi, R. (2017). *Conception d'un doigt artificiel à fibre optique polymérique pour application du toucher de surface textile*. 9.

Pietrosimone, B. G., & Gribble, P. A. (2012). Chronic Ankle Instability and Corticomotor Excitability of the Fibularis Longus Muscle. *Journal of Athletic Training*, *47*(6), 621-626. https://doi.org/10.4085/1062-6050-47.6.11

Ponz, A., Montant, M., Liegeois-Chauvel, C., Silva, C., Braun, M., Jacobs, A. M., & Ziegler, J. C. (2014). Emotion processing in words : A test of the neural re-use hypothesis using surface and intracranial EEG. *Social Cognitive and Affective Neuroscience*, *9*(5), 619-627. https://doi.org/10.1093/scan/nst034

Prevost, A., Scheibert, J., & Debrégeas, G. (2009). Effect of fingerprints orientation on skin vibrations during tactile exploration of textured surfaces. *Communicative & Integrative Biology*, *2*(5), 422-424. https://doi.org/10.4161/cib.2.5.9052

Rabinowicz, E. (1956). When two substances rub against each other, they frequently stick and then slip. The phenomenon accounts for the squeak of bearings, the music of violins and many other sounds of our daily experience. *SCIENTIFIC AMERICAN*, 11.

Rankin, J. K., Woollacott, M. H., Shumway-Cook, A., & Brown, L. A. (2000). Cognitive Influence on Postural Stability : A Neuromuscular Analysis in Young and Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *55*(3), M112-M119. https://doi.org/10.1093/gerona/55.3.M112

Redfern, M. S., Muller, M. L. T. M., Jennings, J. R., & Furman, J. M. (2002). Attentional Dynamics in Postural Control During Perturbations in Young and Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *57*(8), B298-B303. https://doi.org/10.1093/gerona/57.8.B298

Riley, M., Mitra, S., Stoffregen, T., & Turvey, M. (1997). Influences of Body Lean and Vision on Unperturbed Postural Sway. *Motor Control*, *1*, 229-246. https://doi.org/10.1123/mcj.1.3.229

Romo, R., & de Lafuente, V. (2012). Conversion of sensory signals into perceptual decisions. *Progress in Neurobiology*, 35. https://doi.org/10.1016/j.pneurobio.2012.03.007

Salinas, E., Hernández, A., Zainos, A., & Romo, R. (2000). Periodicity and Firing Rate As Candidate Neural Codes for the Frequency of Vibrotactile Stimuli. *The Journal of Neuroscience*, *20*(14), 5503-5515. https://doi.org/10.1523/JNEUROSCI.20-14-05503.2000

Saradjian, A. H., Teasdale, N., Blouin, J., & Mouchnino, L. (2019). Independent Early and Late Sensory Processes for Proprioceptive Integration When Planning a Step. *Cerebral Cortex*, *29*(6), 2353-2365. https://doi.org/10.1093/cercor/bhy104

Saradjian, A. H., Tremblay, L., Perrier, J., Blouin, J., & Mouchnino, L. (2013). Cortical facilitation of proprioceptive inputs related to gravitational balance constraints during step preparation. *Journal of Neurophysiology*, *110*(2), 397-407. https://doi.org/10.1152/jn.00905.2012

Sarma, H. (2020). *A comparative study of the toe print and fingerprint distribution in indo Mongolian race*.

Sherwood, D. E., Lohse, K. R., & Healy, A. F. (2020). The effect of an external and internal focus of attention on dual-task performance. *Journal of Experimental Psychology:*

Human Perception and Performance, *46*(1), 91-104. https://doi.org/10.1037/xhp0000698

Shumway-Cook, A., & Woollacott, M. (2000). Attentional demands and postural control : The effect of sensory context. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *55*(1), M10-16. https://doi.org/10.1093/gerona/55.1.m10

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The Effects of Two Types of Cognitive Tasks on Postural Stability in Older Adults With and Without a History of Falls. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *52A*(4), M232-M240. https://doi.org/10.1093/gerona/52A.4.M232

Sipp, A. R., Gwin, J. T., Makeig, S., & Ferris, D. P. (2013). Loss of balance during balance beam walking elicits a multifocal theta band electrocortical response. *Journal of Neurophysiology*, *110*(9), 2050-2060. https://doi.org/10.1152/jn.00744.2012

Sohrabpour, A., Yunfeng, L., & Bin, H. (2015). Estimating underlying neuronal activity from EEG using an iterative sparse technique. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference*, *2015*, 634-637. https://doi.org/10.1109/EMBC.2015.7318442

Solis-Escalante, T., Van der Cruijsen, J., De Kam, D., Van Kordelaar, J., Weerdesteyn, V., & Schouten, A. C. (2019). Cortical dynamics during preparation and execution of reactive balance responses with distinct postural demands. *NeuroImage*, *188*, 557-571. https://doi.org/10.1016/j.neuroimage.2018.12.045

Starr, A., Mckeon, B., Use, N. S., & Burke, D. (1981). Cerebral potentials evoked by muscle stretch in man. *Brain*, *104*(1), 149-166. https://doi.org/10.1093/brain/104.1.149

Stelmach, G. E., Zelaznik, H. N., & Lowe, D. (1990). The influence of aging and attentional demands on recovery from postural instability. *Aging (Milan, Italy)*, *2*(2), 155-161. https://doi.org/10.1007/BF03323910

Striem-Amit, E., & Amedi, A. (2014). Visual Cortex Extrastriate Body-Selective Area Activation in Congenitally Blind People “Seeing” by Using Sounds. *Current Biology*, *24*(6), 687-692. https://doi.org/10.1016/j.cub.2014.02.010

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm : A User-Friendly Application for MEG/EEG Analysis. *Computational Intelligence and Neuroscience*, *2011*, 1-13. https://doi.org/10.1155/2011/879716

Tang, W., Liu, R., Shi, Y., Hu, C., Bai, S., & Zhu, H. (2020). From finger friction to brain activation : Tactile perception of the roughness of gratings. *Journal of Advanced Research*, *21*, 129-139. https://doi.org/10.1016/j.jare.2019.11.001

Taubert, M., Draganski, B., Anwander, A., Müller, K., Horstmann, A., Villringer, A., & Ragert, P. (2010). Dynamic properties of human brain structure : Learning-related changes in cortical areas and associated fiber connections. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *30*(35), 11670-11677. https://doi.org/10.1523/JNEUROSCI.2567-10.2010

Taubert, M., Lohmann, G., Margulies, D. S., Villringer, A., & Ragert, P. (2011). Long-term effects of motor training on resting-state networks and underlying brain structure. *NeuroImage*, *57*(4), 1492-1498. https://doi.org/10.1016/j.neuroimage.2011.05.078

Urgesi, C., Candidi, M., Ionta, S., & Aglioti, S. M. (2007). Representation of body identity and body actions in extrastriate body area and ventral premotor cortex. *Nature Neuroscience*, *10*(1), 30-31. https://doi.org/10.1038/nn1815

Valbo, A. B., Olausson, H., Wessberg, J., & Kakuda, N. (1995). Receptive field characteristics of tactile units with myelinated afferents in hairy skin of human subjects. *The Journal of Physiology*, *483*(Pt 3), 783-795. https://doi.org/10.1113/jphysiol.1995.sp020622

Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological Research*, *71*(2), 192-200. https://doi.org/10.1007/s00426-005-0018-2

Wallis, J. D. (2007). Orbitofrontal cortex and its contribution to decision-making. *Annual Review of Neuroscience*, *30*, 31-56. https://doi.org/10.1146/annurev.neuro.30.051606.094334

Weber, A. I., Saal, H. P., Lieber, J. D., Cheng, J.-W., Manfredi, L. R., Iii, J. F. D., & Bensmaia, S. J. (2013). Spatial and temporal codes mediate the tactile perception of natural textures. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(42), 17107-17112. https://doi.org/10.1073/pnas.1305509110

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait : A review of an emerging area of research. *Gait & Posture*, *16*(1), 1-14. https://doi.org/10.1016/S0966-6362(01)00156-4

Wulf, G., Höß, M., & Prinz, W. (1998). Instructions for motor learning : Differential effects of internal versus external focus of attention. *Journal of Motor Behavior*, *30*(2), 169-179. https://doi.org/10.1080/00222899809601334

Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning : A review. *Psychonomic Bulletin & Review*, *8*(4), 648-660. https://doi.org/10.3758/BF03196201

Zeharia, N., Hofstetter, S., Flash, T., & Amedi, A. (2019). A Whole-Body Sensory-Motor Gradient is Revealed in the Medial Wall of the Parietal Lobe. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *39*(40), 7882-7892. https://doi.org/10.1523/JNEUROSCI.0727-18.2019