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Walking on virtual surface patterns changes muscular activity

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Abstract. Current designs of structures often involve creative uses of materials and colours. While it is well known that patients with balance related disorders can experience negative effects through perceptual perturbations, the connection from these effects to physical changes still remains unclear. This paper therefore showcases the gait changes induced by walking on potentially irritating virtual surface patterns. Muscular Data from nine healthy young participants point towards a more careful and insecure gait style when confronted with such a pattern. Inhibitions of forward movement are induced by fluctuations in the activity of the musculus rectus femoris and a breaking action by the biceps femoris. This implies a direct connection of visual disturbances to human gait which is especially important for the control of assistive devices that should include an integrated detection of gait relevant visual patterns to compensate patients' uncertainties.

Keywords: human gait, muscular activity, visual perturbations, perception, virtual reality, control strategies

1 Introduction

In the last decades, rising life expectancy and an older average population lead to an increase of disabilities. An extensive survey ("Repräsentativbefragung zur Teilhabe von Menschen mit Behinderungen Zusammenfassung") conducted by the German Institute for applies social sciences from 2017 to 2021 revealed an increase of people with disabilities of 9% between 2009 and 2017 [1]. In Germany alone 9.4 % of the population had the status of "severely disabled" [2] – which means 7.8 million people were affected in the year 2021. Globally, the World Health Organization (WHO) estimates 1.3 billion people to be affected by a disability in 2021 [3], which accounts for 16 % of the population.

Based on three dimensions defined by the WHO, the Center for Disease Control and Prevention created a definition of the term "disability": "any condition of the body or mind (impairment) that makes it more difficult for the person with the condition to do certain activities (activity limitation) and interact with the world around them (participation restrictions)" [4]. Especially the dimensions of activity limitation and participation restrictions are factors that affect how our environment - in which we act in - is designed. Within our highly urban-centered environment, navigating through and being surrounded by architecture - that is often designed to balance functionality and aesthetics - is part of our everyday lives.

Many architectural design properties either contain (e.g., through colouring) or create patterns (e.g., through light and shadows). Research has shown that complex, repetitive, or high contrast patterns can impair the well-being by creating a variety of perceptual perturbations in people with or without specific disorders [5] [6]. Such patterns induce visual discomfort such as annoyance, irritations, distractions, as well as eye strain, and headaches. Flickering light, such as created by walking though light and shadow patterns, has shown to trigger a variety of symptoms for people who experience migraine, epilepsy or a strong sensory photosensitivity.

Photosensitivity is a visual sensitivity disorder response to light stimuli, intermittent light sources and complex stimuli, however almost all patients suffering from this condition are sensitive to flickering light or certain patterns [7]. Bridge parapet railings and other structural elements commonly create such linear high contrast patterns.

Another group of people that are affected by patterns are people with vestibular disorders. Research has shown, that complex, repetitive, or high contrast patterns influence the balance and gait of people with "sensory and/or information processing differences" [8]. For example, Leonards and colleagues (2015) found that patterns on the floor lead to a deviation from the desired movement direction [9]. This might arise due to misinterpretation of the environment (e.g., perceiving barriers, obstructions, curbs, edges of steps or holes) that can lead to imbalance [5], as well as other behavioral changes. Another possible explanation for discomfort and other problems could be so-called "discomfort glare" which causes visual fatigue [8].

Glare is described as a visual difficulty experienced in the presence of significantly brighter light than the eyes have adjusted to. A new guideline published only recently in October 2022 by the British Standards Institution (BSI) specifically states: "Building designers should design to avoid glare from daylight or artificial light sources." [8].

As proposed in [10] this calls for in depth investigations to link perception and human motor responses. To understand this relation not only perceptual but also biomechanical measurements are required. It is known that emotional states can change postural control and gait style [11] [12][13][14] - however these works mainly focused on fear of heights. To this point there is no clear connection between visual perception of surface patterns and human gait, however there are known effects of such patterns on balance control, such as the moving room illusion which can cause balance problems or even falls [15]. This is especially problematic for patients with balance disorders or elderly as they are specifically prone to falls. Visually induced gait style changes or balance problems also have to be considered during the design of assistive devices for walking. While some of these systems feature biologically inspired balance support [16] [17] or improve balance support after slippage [18] their suitability to recover from visual perturbations still has to be evaluated. As a prerequisite to find robust controllers for assistives it has to be understood how humans react to visual patterns in the first place. It is expected that the muscular activity of humans being subjected to such visual disturbances will change to promote a more careful and insecure gait style. This should also lead to a reduction in vertical excursion of the body centre as well as an increase in lateral excursion.

2 Method

To test the effects of virtual surface patterns on human gait we used an improved version of the setup presented in [19]. These improvements involved more processing power and a wireless head-mounted display (HMD) which increases the immersion and reduces the risk of stumbling over the HMD's cable. We further decided to change the virtual environment to an urban setting to increase realism. The experiment was conducted following the Declaration of Helsinki and approved by the Ethics board of Technische Universität Darmstadt (EK83/2022).

2.1 Virtual environment

Participants where placed in an immersive virtual environment using a virtual reality (VR) headset (HTC Vive Pro Eye, Valve, Bellevue, US & HTC, Taoyuan, Taiwan). The VR contained a simple, pre-built model of a major city with high buildings, roads, and skyscrapers and a custom made footbridge on which participants had to walk.

The pattern of the bridge and the colour of the pattern were varied between trials. Figure 1 shows the applied patterns in their greyscale and colour variant. The colours blue and orange were chosen to maximize the contrast between the colours. The bridge had waist-high railings with with few, equally spaced pillars to clearly mark the end of the bridge while avoiding a frequency effect.

For each participant the headset position and rotation were logged.

2.2 Participants

Twelve participants (5 female, 7 male) with either or normal or corrected to normal vision took part in the experiment. They were between 19 and 33 years of age ($\mu = 23.42$, $med = 22$, $\sigma = 4.25$) and ranged from 156 cm to 190 cm in body height ($\mu = 174.0$, $med = 174.5$, $\sigma = 9.43$). Their body weights were all between 50 kg and 89 kg ($\mu = 67.83$, $med = 67.0$, $\sigma = 12.78$). None of the

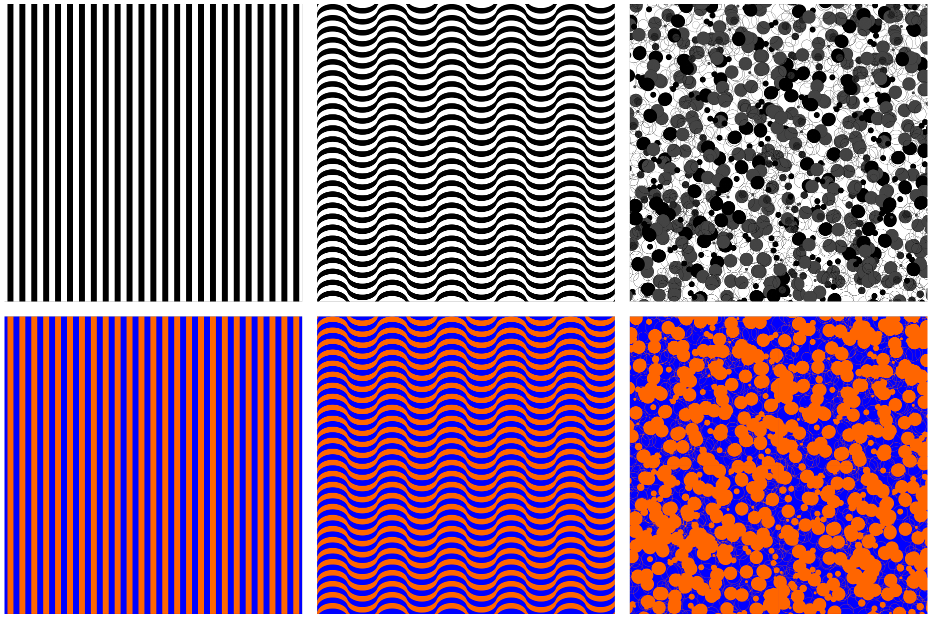

Fig. 1. Patterns applied to the surface of the bridge in VR. **Left** - straight lines. **Center** - Lisbon pattern motivated in [6]. **Right** - random control pattern. Additionally a solid grey surface colour was used as a control condition.

participants had any physical disabilities, two reported to be afraid of heights. Six participants reported not to have any previous experience with virtual reality.

Two participants were excluded due to technical difficulties during the experiment.

2.3 Measurement equipment

Biomechanical measurement devices were utilized to record relevant gait parameters. The participants were therefor equipped with 16 wireless surface electromyography (EMG) sensors (Trigno Avanti, Delsys, Natick, US) which were placed perpendicular to the muscle fibers on the muscle belly of eight gait relevant muscles per limb, including the musculus tibialis anterior (TIB), m. soleus (SOL), m. gastrocnemius lateralis (GAS), m. vastus medialis (VAS), m. rectus femoris (RCF), m. biceps femoris (BCF), m. tensor fasciae latae (TFL), and m. gluteus maximus (GLM). Skin preparation included cleaning of the skin with alcohol. The rectangular electrodes (27 * 37 * 13 mm, mass 14 g) were attached with an adhesive. The sensors feature four silver bar contacts with an intraelectrode distance of 10 mm and collected data with a sampling rate of 1926 Hz. Further, each sensor contained a 3D gyroscope (148 Hz).

We also collected movement data using a 9 camera-based motion capture system (Qualisys Oqus). For this we used a full body marker set consisting of 19 passive reflective markers. Additionally, the head movement was tracked using the position and rotation of the Head-mounted Display (HMD) that are logged by the VR system. This paper however focuses on the analysis of the EMG data, leaving the measurements of the latter two systems for future studies.

2.4 Measurement protocol

After preparation the headset was adjusted to the participant and the participant had time to get familiar with the VR. Each participant went through all conditions in a randomized order to avoid order effects. Within each condition participants performed five trials to increase the amount of available data. Typically each trial contained three full gait cycles per leg plus an initiation cycle. Since this study focuses on stable gait, the initiation cycle was neglected. Every condition featured a virtual bridge with one of the surface patterns depicted in Figure 1, while the baseline condition took place on a neutral grey surface.

2.5 Data processing

EMG data were processed using the method outlined in [20]. The raw signal was demeaned to eliminate potential offsets, bandpass-filtered (10-450 Hz, fourth order Butterworth) and time-normalized over one gait cycle. The time-normalized signal was then highpass-filtered (6 Hz, second order Butterworth) and aggregated over each condition.
Individual strides were identified based on gyroscope-stride identification [20]. Thus, gyroscopic data in the sagittal plane from three sensors (TIB, SOL, and GAS) were combined to obtain a reliable measure for the orientation of the shank. Following [20] the heel-strike was defined using the first zero-passing of the combined angular velocity after a highly negative combined signal. Further, the first stride of each leg was neglected to avoid gait initiation effects. Lastly the Grand Mean [20] over all conditions and participants was calculated and used for detailed analysis.

3 Results

With typically 6 strides per trial (3 left, 3 right), participants took 60 gait cycles per condition. Between these conditions, clear changes in muscular activity could be observed (see Figures 2 and 3).

The biarticular extensor muscles (GLM, VAS, and SOL) of the right leg generally showed an increased peak activation during the start of the swing phase (roughly at 60 % of the gait cycle) (see figure 6). While the GLM showed its largest difference during the coloured Lisbon condition (see figure 1), the activity of the SOL increased by more than 10 % for all conditions but the greyscale Lisbon and random pattern. In the left leg, the extensors indicate that the VAS is shows a more fluctuating behavior in all conditions, while GLM and SOL remain within range of the control (see figure 7). The left GLM however

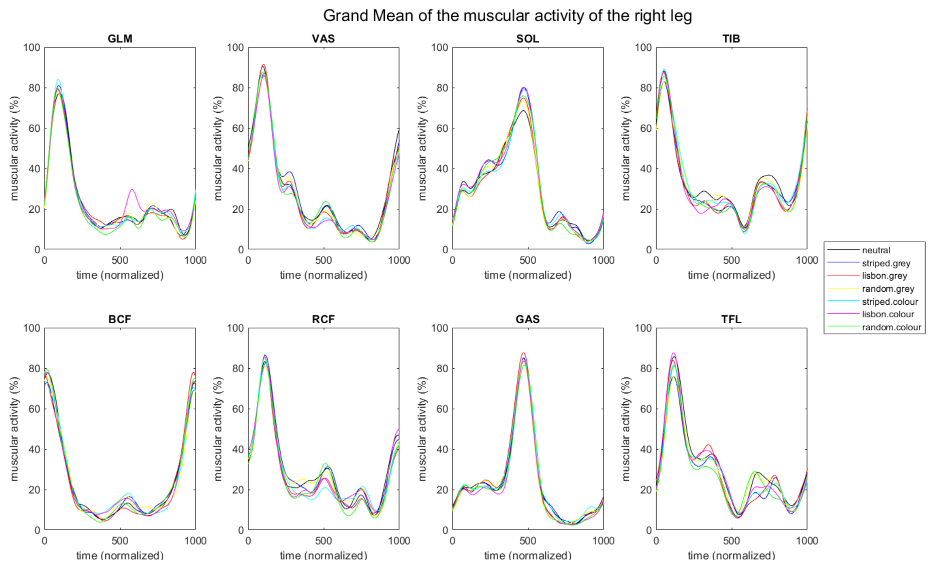

Fig. 2. Grand mean of the muscular activity of the right leg per condition. Note the secondary peak in GLM activation during the coloured Lisbon condition and the earlier activation of the TFL during the onset of the swing. Also the SOL shows more activity in all conditions when compared to the baseline. These findings point towards a small disruption during the gait cycle that is mainly countered by the unilateral extensor and the lateral muscles.

shows the tendency of a reduction during onset of swing. The left TFL showed a noticeable reduction in activity during the standing phase, while the right TFL increased shortly after the heelstrike. While the flexor muscles (BCF, RCF, and GAS) of the right leg do not show significant changes, the flexors on the left leg fluctuate noticeably around their respective activity during control. While BCF tends to be activated more during the gait cycle, the RCF shows a reduction during the transition between standing and swinging. The left GAS also peaks during this time. The right TFL shows tendencies towards a reduction in activity during the swing phase for the Lisbon and striped conditions (see figure 6). However it peaks for both the greyscaled and the coloured striped patterns around the same time. The left TFL does not show any changes above 10 %.

Considering the rate of change in muscular activity in both legs, figures 4 and 5 showcase the actuation patterns. It is noticeable that especially the GLM and SOL respond to all surface patterns with a higher rate of change over time during activation. These findings could indicate a reduced vertical excursion of the Centre of Mass (COM) as well as an increase in lateral excursion. In a preliminary effort the geometrical mean of the pelvis was calculated based on Motion Capture data to approximate the COM. The trajectory of this approximate COM did not significantly vary between the conditions.

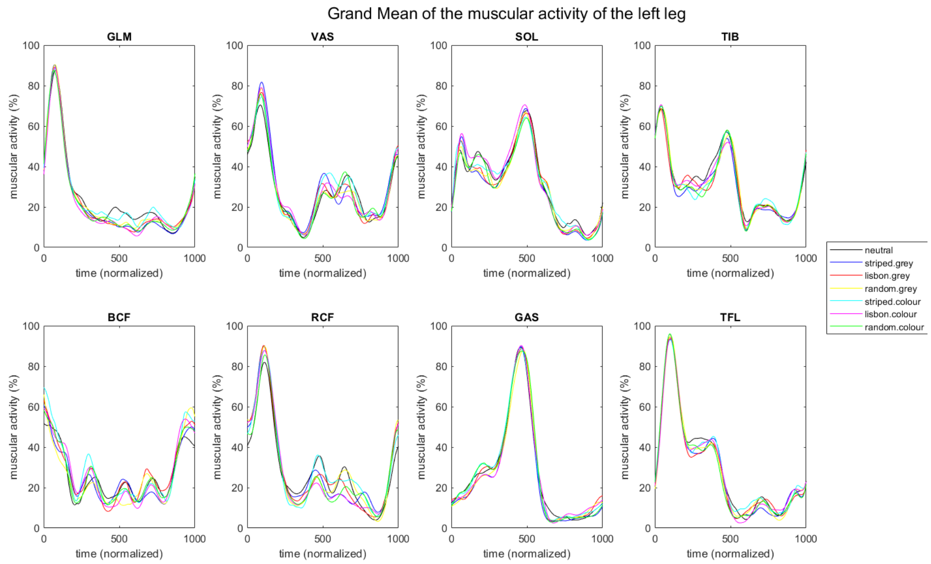

Fig. 3. Grand mean of the muscular activity of the left leg per condition. The BCF shows higher but more erratical activation patterns when confronted with any of the surface patterns, while the RCF shows lower activation especially during the onset of the swing. This could indicate a reduced vigor of the swing leg.

All participants reported that they felt most uncomfortable during walking on both the coloured and the greyscale Lisbon pattern.

4 Conclusion

So far, the influence of patterns on people with migraine, photosensitive epilepsy, as well as vestibular disorders have not been taken into account, yet, when designing architectural structures in terms of their trigger-ability. Even though it is well known that people with conditions mentioned above can suffer from visual patterns, the recently published guideline by the BSI is the first to address these issues. As the perception of structures is highly individual, inclusive architecture only recently started to arise. Today, architecture and design slowly start to incorporate inclusive ideas into their work.

Although the trigger-ability of high-contrast patterns on many different conditions are widely known, there is very few research aimed at uncovering the effects of patterns created by our urbanized environment. The effect of surface patterns on human gait are especially important for patients with diseases related to balance or visual perception. As only healthy young participants were admitted to this study the results are not directly transferable to patients or the elderly. It would need further research focusing directly on the target group to fully capture the clinically relevant effects of visual perception on human gait.

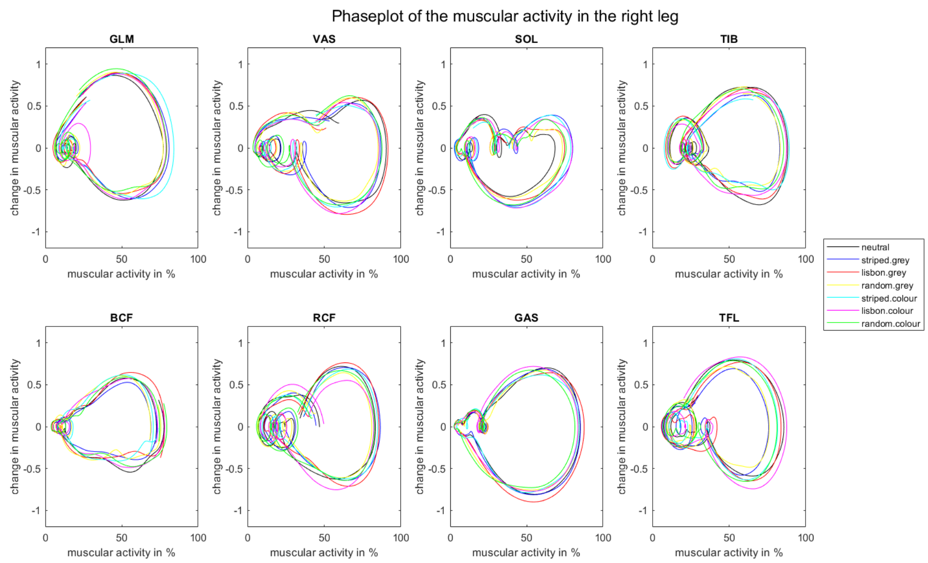

Fig. 4. Phaseplot of muscular activity for different surface conditions.

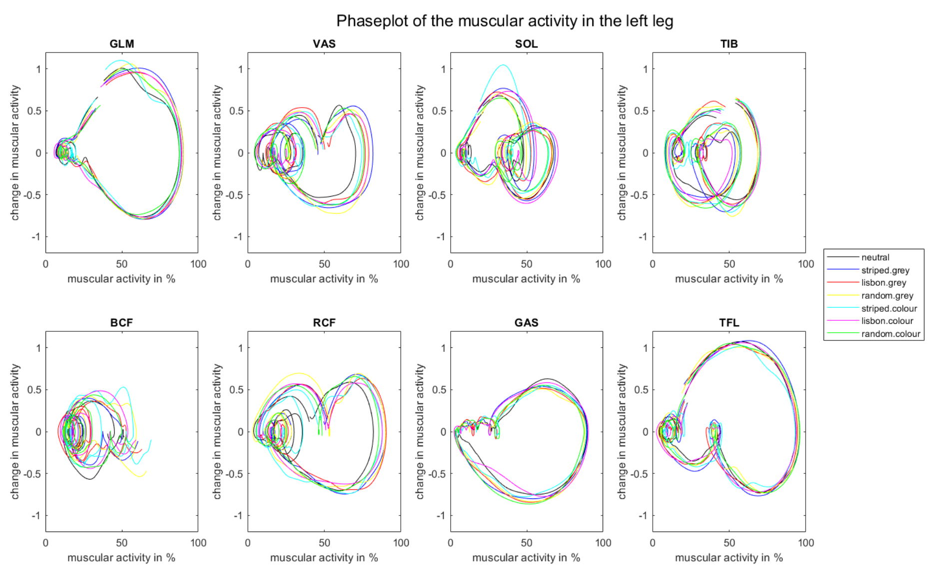

Fig. 5. Phaseplot of muscular activity in the left leg for different surface conditions.

While the validity of these results may also be subject to the limited immersion of HMDs and could partly be explained due to the uncertainty induced by the HMD itself, the changes in muscular activity during walking on virtual surface patterns indicate a more careful and insecure gait style. This is especially high-

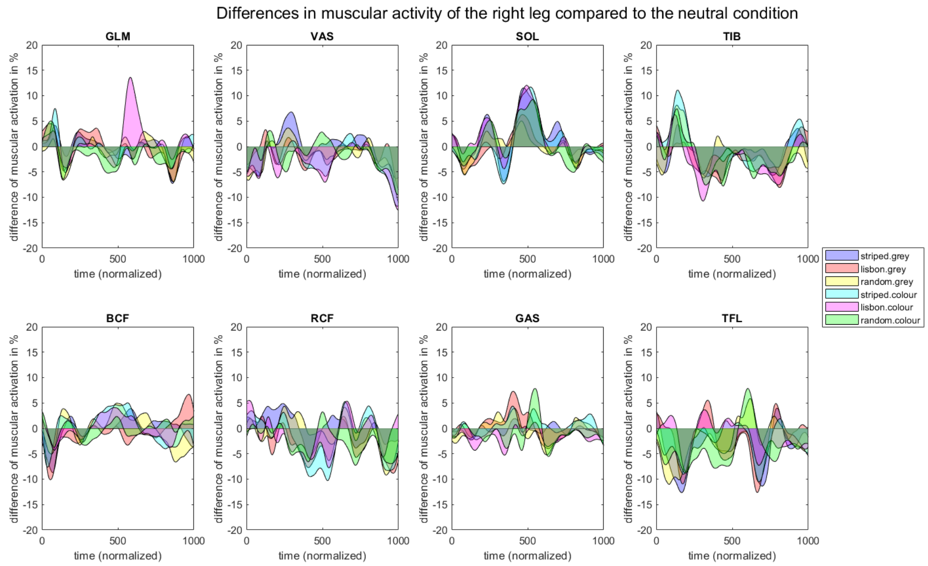

Fig. 6. Difference of the muscular activation in the right leg between each surface condition and control (solid grey surface). While GLM and SOL show increased activity during the beginning of the swing phase in some conditions, the flexor muscles do not show significant changes. Interestingly, the activation of the lateral TFL is generally reduced with a little peak at the start of the swing phase.

lighted by the behaviour of the left BCF which shows higher fluctuations during the conditions involving surface patterns. This could be interpreted as a stuttering breaking action which inhibits the forward movement of the leg. An insecure gait style also becomes apparent as also the left RCF muscle shows a fluctuation and tends to reduce its activation during the begin of the swing phase. This indicates a forward swing with less vigor. Further evidence for an insecure gait style stems from the increase in the activity of the right GLM during the onset of the swing in the coloured Lisbon condition. This would lead to a short but noticeable breaking action of the leg. Surprisingly, many muscles of the left leg (esp. GLM, RCF, SOL, and TIB) showed a reduction in their activity. Since GLM, VAS, and SOL are extensor muscles, this points towards a stiffer gait style which should lead to a reduction in vertical body center excursion. Combined with the information about the BCF and RCF this could indicate a more cautious gait style. Since the preliminary analysis of the approximate COM yielded no results, both an increase in lateral or a decrease in vertical COM excursion cannot be assumed. However, the findings call for a further in-depth analysis of the Motion Capture and the head tracking data, since the upper body sway could differ from the COM excursion.

It is therefore possible that humans change the control strategy of their limbs during walking over irritating surface patterns. This fits well into the literature

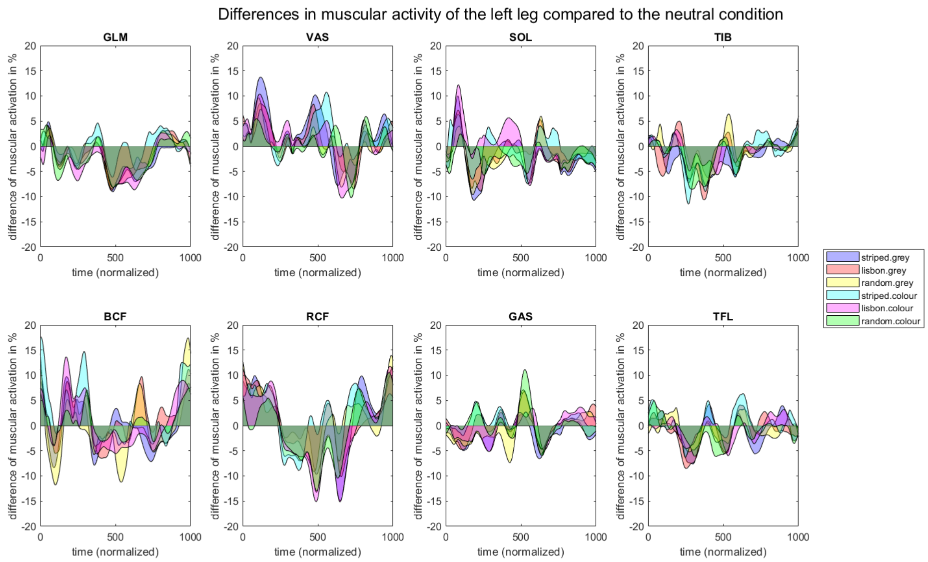

Fig. 7. Difference of the muscular activation in the left leg between each surface condition and control (solid grey surface). Especially the flexor muscles BCF and RCF show a fluctuating behaviour which points towards a less efficient gait. This could be attributed to uncertainties induced by the surface patterns.

on the impact of emotions and insecurity on gait and highlights the importance of inclusive structural design. Especially for patients, these patterns can prove to be a huge challenge. This also has to be considered by a controller of an exoskeleton or an active prosthesis to avoid tripping or falls.

Further investigations can be used to develop supportive structural designs and also enhance the control mechanisms of assistive devices. While more research is needed to get a deeper insight into the mechanisms of disturbances by visual patterns, this study showed an influence of visual patterns on gait and behavior even in young and healthy participants.

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