A Wearable Vibrotactile Interface for Unfavorable Posture Awareness Warning

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Abstract: We present the concept of a vibrotactile interface with up to 13 tactors (vibration motors) that are distributed over the full body to warn industry workers when taking unfavorable postures. The developed system is to be integrated into a motion capture workwear for industry workers to serve as posture feedback system to prevent unfavorable or even harmful postures. Such postures are a risk factor for musculoskeletal disorders (MSD), especially among older adults. We evaluated the vibrotactile system with 11 subjects to identify the optimal notification vibration sequences (regarding pulse length and repetition) and the accuracy of the location-dependent perception. Results indicate that the optimal pulse length is about 150 ms and is repeated 2 or 3 times within the sequence for maximum attention.

1 INTRODUCTION

Industry workers regularly perform harmful or dangerous postures during their work shifts (as shown exemplarily in Figure 1). These unfavorable postures can – when performed regularly – lead to musculoskeletal disorders (MSD) such as chronic back pain, especially among workers in the second half of life. Such MSDs are a primary cause of absence from work due to illness and early retirement in physically demanding occupations. According to (Punnett and Wegman, 2004), MSDs are the most significant category of work-related illnesses although a direct comparison between countries is difficult. The treatment of MSDs amounts to considerable costs for the public health systems of various countries, e.g., the Federal Statistical Office of Germany reports costs of 420 € per citizen for the year 2015 (Statistisches Bundesamt, 2017; Walker et al., 2003).

Even if the causes of MSDs are not always occupational causes, heavy physical work such as manual handling and lifting is often considered a risk factor for the emergence of musculoskeletal disorders (Amell and Kumar, 2001; Hoy et al., 2010; Matsui et al., 1997). Thus, prevention measurements become a necessity, e.g., as part of the corporate health management in industrial companies with physically hard-working employees.

Figure 1: Shipyard welders working in awkward poses.

It is an ongoing task of the corporate health management to continuously assess psychological and physical risk factors of every workplace and every working individual. For the early detection of such risk factors for occupational diseases of the musculoskeletal system, a measuring suit that includes 15 distributed intelligent sensor nodes has been developed (Lins et al., 2015). Each of these nodes incorporates a 6-DOF inertial measuring unit (IMU) with accelerometer and gyroscope that together measure relative linear and angular acceleration. The measuring suit is integrated into ordinary work clothes to not interfere with the daily work. The nodes are small, lightweight and can be cleaned with the work clothes in industrial washing machines. The collected data of the inertial sensors can be analyzed by occupational physicians to derive individual risk factors for MSDs using specialized software. Additionally, the analyz-

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ing software on the node or central unit can identify critical postures to give the wearer an immediate feedback on her or his possibly harmful postures. Then the employee might be able to actively take a more ergonomic pose or interrupt the work for a moment to recover.

In this work, we present a vibrotactile interface (VTI) that is integrated into workwear together with this unobtrusive motion capture sensor suit (Lins et al., 2015) so that wearers are alerted whenever performing unfavorable postures. Our approach here enables wearers to be aware of potential harmful postures so that they can decide to improve their pose by themselves. Most approaches rely on a tight-fitting connection between the body and the tactile interface so that it can be assumed that the dampening effect of the clothes is minimal. This is a valid approach for a controlled experimental setting. We pursue a more practical approach and deliberately integrate our VTI into the loosely-fitting workwear. For such approach, necessary parameters as well as localization-dependent perception accuracies are missing, which we investigate in this work. Also, it is challenging to integrate a VTI with a non-trivial number of tactors (that are required for sufficient precision) unobtrusively into the workwear and at the same time make the system electrically stable, robust and mobile usable a full workday. The availability throughout the day may suffer if the vibration motors are frequently used as every motor requires 150 mA while vibrating. Thus, to improve the runtime of the VTI, an energy efficient (short and recognizable) vibration pattern and well-suited positioning of the VTIs must be identified.

The outline of this paper is as follows: In Section 2 we inspect some of the related work conducted regarding the applicability and efficient use of vibrotactile interfaces. In Section 3, we introduce our concept and the prototype in detail. In Section 4, we present the first results of our experiment to identify the optimally perceived vibration parameters (length and repetition of pulse codes) as well suited positioning in terms of perception accuracy. In Section 5, we discuss our findings critically and give an outlook and identify further steps in Section 6.

2 RELATED WORK

Vibrotactile interfaces have been used in various fields, e.g., to guide people. For instance, (Kerdegari et al., 2016) have implemented a helmet for firefighters that helps them to navigate in smoky areas. Piateski and Jones have created a tactile display with a 16-element tactor matrix and have evaluated different patterns for navigation (Piateski and Jones, 2005). Also, (Alahakone and Senanayake, 2010) and (Gopalai and Arosha Senanayake, 2011) have developed and evaluated a back belt containing sensors and tactile actuators for postural control feedback in rehabilitation. In principle, they use inertial sensors to get the back's orientation and generate a tactile feedback with varying strength dependent on the difference in the optimal back orientation. Carvalho et al. present a closely fitting system integrated into a vest (Carvalho et al., 2017). The system incorporates inertial sensors and tactors and can be used to recognize unfavorable poses of the spine.

Due to the practicability of tactile interfaces as an undisturbing notification mechanism, the core parameters for optimizing tactile interfaces are well known: These parameters of vibrotactile perception are amplitude, frequency, timing and location (Van Erp, 2002). However, coding information by amplitude variations is difficult because the range between comfort and pain is small and typically allows only four different levels (Van Erp, 2002; Brell and Hein, 2007). While the sensitivity to frequency is optimally perceived in a range between 150 Hz and 300 Hz (Jones and Sarter, 2008), coding information through frequency-variations is difficult as only nine different levels of frequency are recommended for vibrotactile interfaces (Van Erp, 2002). Coding information in temporal patterns (pulses) gains more precision if the gap and pulse lengths are at least 10 ms long (Van Erp, 2002). Kaaresoja and Linjama have investigated the subjective perception of various pulse lengths of a vibration motor and found that in this particular case the ideal pulse length is 50 ms to 200 ms for getting attention (Kaaresoja and Linjama, 2005). Longer pulses were perceived as annoying. Spatial resolutions for vibrations on the skin is at least 4 cm which should be sufficient for limb-aware warning (Van Erp, 2002).

Many physiological parameters about vibration and tactile perception are well known, and a comprehensive overview about the spatial and temporal sensitivity of the human skin is available through Lederman (Lederman, 1991).

3 SYSTEM DESIGN

The complete system consists of the Motion Capture (MoCap) sensor suit integrated into workwear, a Decision Support System (DSS), and the Vibrotactile Interface (VTI).

3.1 Motion Capture Sensor Suit

Technically, the suit consists of 15 sensor nodes incorporated in the workwear. The nodes are placed in the work clothing so that sufficient coverage of all limbs is achieved. The individual sensor nodes are connected via a wired bus system with a small central unit, which makes the necessary calculations and records the movement data on a memory card. The cables are integrated with the sensor nodes in the clothing so that they are usually not noticed by the wearer. The central unit is about the size of a pack of cigarettes and can be easily stored in a jacket pocket (Lins et al., 2015).

Each sensor node consists of two sensors, which measure the linear acceleration in three dimensions (accelerometer) and the angular velocity (gyroscope) (6-DOF IMU). This sensor data of all sensor nodes are combined by sensor fusion software such that the movement of the wearer can be derived (Wenk and Frese, 2015). In contrast to other measurement suits, the sensors are not directly placed on the skin, which means that the movement of the limb in the suit and the wrinkling of the clothing will cause deviations from the actual movement.

3.2 Decision Support System for Posture Warning

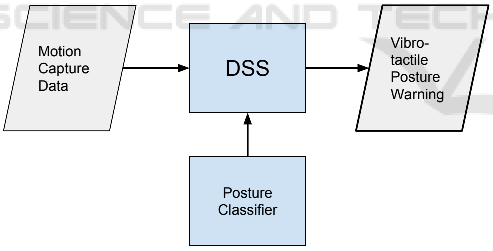

Figure 2: Basic structure of the decision support system. Diamond shapes represent input/output data.

To notify workers in case of unfavorable postures, we aim to integrate a Decision Support System (DSS) into the sensor suit. The DSS is the software component of the vibrotactile feedback system (see Figure 2). It analyses the posture of the suit wearer and generates pulse sequences at appropriate positions on the body. In our concept, the DSS does not yet generate possible alternative poses as in other approaches but warnings of unfavorable postures. It is more appropriate to train the staff so that it is capable of independently taking the most sensible posture, instead of generating alternative postures by an – albeit advanced – computer system.

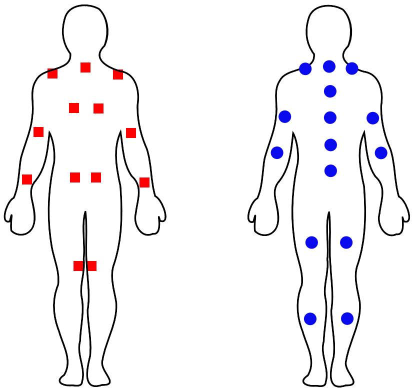

Figure 3: Placement of the tactors (red squares, left) and motion sensors (blue circles, right) on the body (backview).

The system gets the skeletal motion capture data from the suit's sensor fusion component. At first, the motion data is segmented into both movements and static postures (Lins et al., 2018). The postures are then risk rated using a predefined pose classifier, e.g., based on common posture assessment methods, in our case the Ovako Working Posture Analysis System (OWAS) (Karhu et al., 1977).

An improved version of the DSS as outlined in Figure 2 may include a module that can - based on the posture and the current work - guide the wearer to a less awkward position through a custom vibrotactile code. Spelzman et al. have developed such system for snowboard training (Spelmezan et al., 2009).

3.3 Vibrotactile Interface

Our tactile display used in this work consists of 13 tactors placed next to joints and anatomic references where the skin is relatively thin and location sensitive (see Figure 3). The anatomical points for the tactor placement are the neck, shoulders, elbows, wrists, the lower end of shoulder blades, left and right of the lumbar spine, and on the inner side of the knees. Due to the possibly higher perception of vibration near bones, they might be used as a resonance body and thus strengthen the perception of the vibration.

The vibration motor type used here is a rototactor (type EKULIT VM 0610 A 3.0) that runs at a fixed vibration frequency of 167 Hz, which is within the optimal perception range (Jones and Sarter, 2008). The vibration motors heads can rotate freely. Therefore they are encased before their integration into the workwear suit. For this reason, we 3D-printed fitting plastic caps (see Figure 4 on the right) that cover the spinning head and most of the motors. The caps are fixed on the motors, so they are not vibrating *within* the caps, but the head can spin freely.

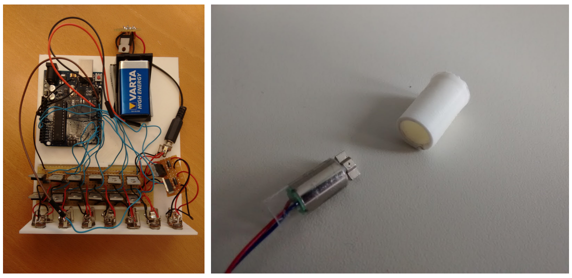

Figure 4: Opened prototype of the central unit (left) and a vibration motor with its plastic cap (right).

Figure 5: Integration of the tactors into regular workwear.

The complete vibrotactile interface is integrated into standard industrial workwear (*rofa Bekleidungswerk*) with cable canals and velcro closures for the tactors. Some tactors are additionally fixed with tape. Every tactor is connected to the central unit (see Figure 4 on the left) using phone jack connectors. Hence it is relatively easy to connect and disconnect the central unit from the suit.

4 EVALUATION

The experiment aimed to determine the optimal range of the following two vibration parameters to achieve a high perceptional accuracy. These parameters are the number of repetitions n of a single pulse P within a warning sequence S as well as the optimum length p_t of these individual pulses (see Figure 6). The pause interval between pulse repetitions was chosen to be p_t as well.

The experiments were carried out as part of a short pilot study with a total of 11 subjects (8 male, 3 female).

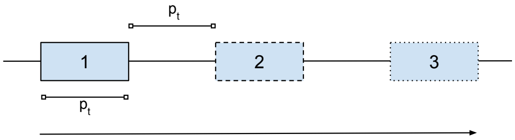

Figure 6: A pulse sequence S consisting of one to three pulses P each having length and pause interval p_t.

4.1 Experimental Setup

Subjects were standing upright on two legs (OWAS 112) and had to determine the stimulating position. Throughout the experiment, subjects had to point or mention the limb (for example ”left shoulder”), which were perceived as the most prominent source of vibration. The equality of the perceptions is also a valid answer. The experimenter records the side on which the subject perceived a stronger or more pronounced vibration and the number of the tactor, which the subject has perceived. The sequence of the VTI stimulation positions is defined by a random repetitive vibrational pattern (generated via pseudo-random number generator of the Arduino-based central unit) is used to maximizes the variance of the tested patterns and eliminate potential biases due to the predictability of vibration location. To determine the optimal pulse length and the optimal number of pulse repetitions per alarm sequence, the central unit has been programmed such that a random pair of pulses (e.g., knee left and knee right) are recorded every 10 seconds with a random pulse sequence. Pulse frequency and amplitude were constant. The subject wore headphones listening to pink noise to prevent them identifying the position based on motor-sounds.

4.2 Results

In total we collected 539 evaluable left-right perceptions, each stated as $SP = \{S_L, S_R\}$, of 11 subjects. Of these perceptions 306 samples were with a clearly stronger left or right perception ($S_L > S_R$ or $S_R > S_L$), further called S_{max}.

For all S_{max} we summarized their number of repetitions and pulse lengths (see Table 1 and 2).

Table 1: The ratio of particular pulse sequence repetitions within the strong perceptions, i.e. how many of the S_{max} are sequences with one, two or three repetitions.

Pulse repetitions	1	2	3
Ratio	22.9%	36.9%	40.2%

Table 2: The ratio of particular pulse lengths within the strong perceptions, i.e. how many of S_{max} are sequences with pulse lengths of 25, 50, 100 or 150 milliseconds.

Pulse lengths	25 ms	50 ms	100 ms	150 ms
Ratio	12.7%	20.9%	27.8%	38.6%

These preliminary results show that a pulse sequence with two or three individual pulses, each with a pulse length of 150 ms, is most clearly perceived. This is also in line with the literature values, which were tested directly on the skin (Van Erp, 2002).

However, the exact position of the vibration could be localized correctly only in about 60.8% of the cases. The vibrations on the back were difficult to perceive properly. In particular, the vibration motors in the lumbar region were not perceived at all. The reason for this is likely the loose jacket.

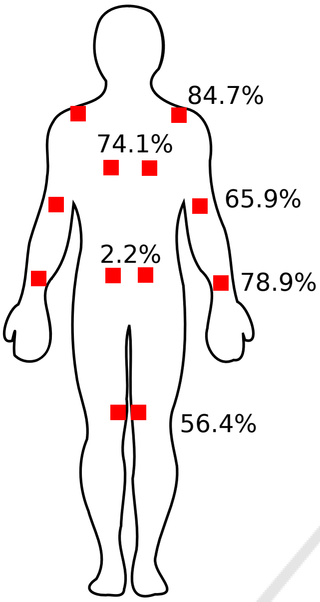

Figure 7: Percentage of correct localizations of the different tactor groups (shoulders, upper arm, wrist, upper back, lower back, knees). The values refer two both left and right side.

Figure 7 shows the accuracy with which the vibrations at the individual body positions could be correctly localized.

5 DISCUSSION

In principle, a vibrotactile interface is suitable for unfavorable posture warning. However, for the vibrotactile interface, which has been tested here, the placement of the tactors is not yet optimal (about 60% correct localization). As one can see, the perception is good at the shoulders and wrists, slightly worse on the arms and the upper back (see Figure 7). The lower back tactor integrated into the jacket is not correctly recognized in nearly every case. Sometimes the subjects report undifferentiated vibrations somewhere on the back. This is probably caused by the jacket that is too loosely on the skin. A similar situation is at the knees but not to this extent. So we can say the vibrations, which were triggered by tactors close to the skin, were perceptible in most cases. If the tactor is only loosely on the skin due to folds or dampening effects of the fabric, the perception is significantly worse. This issue is of great importance if the vibrotactile feedback should communicate postural change hints to the wearer. If the VTI is not precise enough to allow the wearer identify the limbs at risk, a change hint will not be correctly perceived either.

In our pilot study, we have investigated the effect of varying the pulse lengths together with length-adapted pause intervals between two pulses, i.e., $p_t =$ pause. The follow-up study should investigate various pause intervals as well.

Finally, it must be noted that further usability tests are necessary, especially in combination with the previously untested connection to the decision support system, i.e., to address the issue of alarm fatigue (Wilken et al., 2017).

6 CONCLUSIONS AND FUTURE WORK

We presented the concept and the first prototype of a wearable vibrotactile interface (VTI) that is intended for the usage in occupational environments to warn its wearer of unfavorable or even dangerous postures. The VTI can work in conjunction with IMU-based sensor suits that can capture the motion and postures of the user.

As a first step towards a closed-loop sensor and feedback suit for preventing unfavorable postures at work, we built a prototype of VTI and integrated it into standard workwear. We conducted a pilot study to identify the most strongly perceived vibration parameters (length and repetition of pulse codes). Additionally, we evaluated the location accuracy of the perceived vibrations. We recommend a pulse sequence of two 150 ms pulses for posture warning. A third pulse would not increase the perceptions much but cost additional energy. A pulse length of 200 ms could improve the perception of an alert, which should be verified in an additional study. Longer pulses would probably irritate the users as noted by Kaaresonja and Linjama (Kaaresoja and Linjama, 2005).

Our findings indicate that the accuracy of such VTI within the workwear vary substantially on the body, so we propose changes for an improved version of the VTI. First, the tactors of the lumbar back must be integrated into the waistband of the suit's trousers, because the current placement on the jacket's back has proved itself practically useless (see 2.2% in Figure 7). Then, the number of tactors on the back can be reduced to minimize the complexity of the system in regards to cabling. Finally, we will investigate the possibility to encode guidance information through vibrotactile codes (pulse lengths, repetitions, and variations in the pause interval), which guide users to better manual handling and avoidance of constrained postures.

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