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Utilisation of tactile sensors in ergonomic assessment of hand–handle interface: a review

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Abstract. Many ergonomic studies deal with comfort or try to find optimal parameters for tool design. Most of these studies also emphasise the importance of coupling between hand and handle. In order to collect objective data about hand–handle interface pressure, tactile sensors can be used. A trade-off between sensor dimensions, sensel density, robustness, and accuracy must be considered while choosing between commercial tactile sensors for ergonomic investigations. Based on literature from the last two decades, the main aspects of tactile sensors usage are highlighted.

Key words: hand–handle interface, force sensitive resistors, pressure mapping.

INTRODUCTION

Hand-handle interface is the link between the human and the equipment in a work system (Grandjean & Kroemer, 1997; ISO 26800). Therefore, the fit between the human hand and the tool handle is of particular interest of ergonomic intervention. Data about human abilities, limitations and variability must be quantified and applied to the design in order to improve compatibility between the two elements of the work system. Problems arise when trying to quantify experiences such as comfort. First, comfort is highly subjective; second, it is by nature a binary function; and third, human ability to make long term predictions about gripping comfort is doubtful. People tend to overestimate their tolerance of externally applied surface pressure to an extent that could cause tissue damage (Fransson-Hall & Kilbom, 1993). Moreover, the blood flow in the human palm does not correlate with the pressure-pain threshold (Johansson et al., 2002). Therefore, Strasser & Bullinger (2007) suggest a synergism of objective and subjective assessment methods, but assert that data from subjective methods is not reliable and concrete.

There are objective criteria for ergonomic quality assessment due to knowledge about pressure-pain tolerance (Fransson-Hall & Kilbom, 1993), pressure discomfort threshold values (Johansson et al., 1999), and the relationship between blood flow and externally applied pressure (Johansson et al., 2002). In the presence of such criteria, one could find sensors to satisfy said criteria.

Usability of the criteria for interface pressure measurement sensors can be summarized on the basis of Ferguson-Pell et al. (2000), Memberg & Crago (1997) and

Wang et al. (2007). In general, sensors should be: robust in construction, flexible and wearable by design (must not restrict movements or interfere with other sensors), small (≤10 mm in diameter), thin (1 mm thick), high in accuracy (in sense of linearity, hysteresis, repeatability, time constant, effects of temperature, humidity, or curved surfaces), range at least to 50 N, resolution 1 N, able to measure both shear and normal force, low cost, able to allow fast and easy calibration.

In this review, operational issues of capacitive tactile sensors and piezoresistive tactile sensors in hand-handle interface pressure measurement are examined.

Properties of the sensors

In the case of capacitive sensors, a pressure-sensing element (dielectric material between two layers of conductive material) is sandwiched by elastic synthetic layers. Pressure applied to the sensor will reduce the gap between the layers of conductive material and thus change the sensor's output. A piezoresistive tactile sensor consists of a layer of pressure-sensitive ink (pressure sensitive element), which is applied on conductive material (leads). The leads and the pressure sensitive element are then sandwiched by elastic synthetic layers. Only one manufacturer (Novel Gmbh, Germany) of capacitive sensors was mentioned in the scientific literature while three manufacturers (Tekscan Inc, USA; InterLink Electronics, USA; Verg Inc, Canada) were mentioned in the case of piezoresistive sensors.

Sensors for interface pressure measurement come either in the form of a single sensor or a sensor matrix. In case of a sensor matrix, flexible tactile sensors as thin as 0.1 mm are printed on polyester sheets either horizontally or vertically. When two sheets are laminated together, the intersections of horizontally and vertically printed tactile sensors create a sensing element (sensel). Therefore, most commercial sensor matrixes have higher sensel density than single sensor arrays. Utilisation of sensor matrixes also allows to acquire data about applied force, pressure and contact (see Fig. 1).

Sensors can be applied either on a tool handle, hand or a glove. A sensor matrix is usually shaped as a simple rectangle which limits its applications in hand-handle interface measurement. Handles are usually not shaped as simple cylinders. More complex handles will cause sensors to bend or wrinkle. Bending induced noise has been reported by Kutz et al. (2007), Wang et al. (2007) and Lemerle et al. (2008). Therefore, a more complex form of sensor is needed to conform with non-cylindrical or cone shaped handles. Both Novel Gmbh (Lemerle et al; 2008) and Tekscan Inc (Wang et al., 2007; Mastalerz et al., 2009; Vigouroux et al., 2011) produce sensor matrixes where the sensing regions are allocated so that they can be positioned individually. Regions allocated in such a way can be applied to a bare hand or a glove. An example of a sensor matrix with 18 sensing regions (Tekscan 4256) is shown in Fig. 2-B. Another approach is to use a trimmable sensor matrix. However, bending or wrinkling seems to be a concurrent phenomenon in the case of sensor matrixes.

Bending also affects single sensors. Jensen et al. (1991) reported a difference in sensor response between finger and flat surface applied sensors. Fergusson-Pell (2000) states that the effect of curvature becomes evident with radii greater than 32 mm. To avoid bending, it has been suggested to make sensors more rigid. For this purpose, an epoxy dome (Jensen et al., 1991), epoxy dome and base plate (Vecci et al., 2000), epoxy dome and steel base plate (Kargov et al., 2004; Pylatiuk et al., 2006), or fibreglass resin dome (Hall et al., 2008) are used. However, this approach could affect dexterity and be in conflict with sensor usability criteria defined above, but according to Jensen et al. (1991), the sensors were able to conform to the shape of the finger after attaching epoxy domes.

Calibration procedures are shown to have a significant impact on the resolution of the measurement system (Lemerle et al; 2008) and accuracy (Giacomozzi, 2007). Some researchers do not explain calibration methods clearly, but it is common to use a dynamometer (Radwin et al., 1992), known weights (Fellows & Freivalds, 1989; Komi et al., 2006), load cells (Bishu et al., 1993; Vecchi et al., 2000; Kong & Lowe, 2005), a laboratory scale (Kargov et al., 2004), a pneumatic calibration rig (Gurram et al., 1993; Buis & Convery, 1997; Wimer et al., 2004), or a pressure algometer (Hall 1997). Load cells seem to be the most user friendly option in the case of single sensors. The outputs of the sensor and the load cell can be measured simultaneously which allows for fast and easy data collection and linking. In order to simultaneously load and calibrate all sensels, a pneumatic calibration rig or a bladder should be used in the case of sensor matrixes. According to Tekscan's literature, a process of equilibration must be carried out prior to calibration. After equilibration, one could either proceed to calibrate the sensor matrix using known weights or continue to use a pneumatic calibration rig. However, calibration with known weights is reported to be time-consuming and sometimes uncalibrated raw sensor values are used (Hendrich et al., 2010).

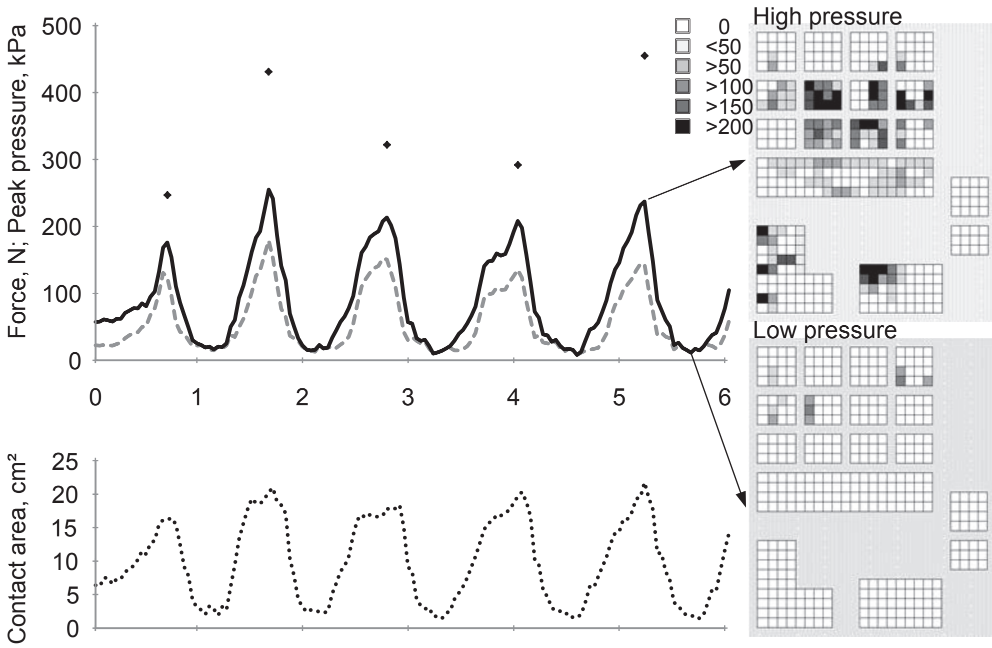

Figure 1. Sample analysis: work cycles (truns) while operating a screwdriver: dots – peak pressure on hand; solid line – force applied by whole hand; dashed line – force applied by fingers; dotted line – contact area; on the right, two GUI outputs are shown (high and low pressure frames), note that sensor regions correspond to Fig. 2-B (Own source, unpublished data).

A change in the sensor output in response to constant weight, force or pressure is called either 'drift' or 'creep'. Hollinger and Wanderley (2006) state that due to resistance drift, force-sensing resistors cannot be used in absolute measurements of force. Wang et al. (2007) are less strict and admit that 'measurement results are acceptable when the force value accuracy is not strictly required'. Komi et al. (2007) argued that drift should not be a problem in grip assessments as the locations and the magnitude of applied force change relatively quickly (see Fig. 1). Sensor output is also sensitive to temperature changes, but this is not a problem in a controlled laboratory environment.

Vecchi et al. (2000) found robustness to be a limiting factor of the Teskscan Flexiforce sensors' (single sensors) usage as the two layers of polyester come detached after numerous tests. Björing et al. (2002) experienced sensor breakdown, Fernandes & Chau (2008) had problems with acquisition of software and unspecified data loss was reported by Lowe and Kong (2007). Therefore, missing or corrupt data is a rare occasion.

Vecchi et al. (2000) conclude that Tekscan Flexiforce sensors 'can overcome some of the common problems of the FSR sensors, especially in terms of linearity, repeatability, and time drift'. Specification of the Tekscan Flexiforce A201 allows $< \pm 3\%$ error in linearity, $< \pm 2.5\%$ in repeatability and drift, $< 5\%$ per logarithmic time scale. Fergusson-Pell et al. (2000) found the drift of 1.7–2.5% per logarithmic time scale, while Hollinger & Wanderley (2006) reported 10.3–11.4% and 4.1% drifts in a period of 240 and 1200 s, respectively. Fergusson-Pell et al. (2000) and Hollinger & Wanderley (2006) used sensors with a different range, therefore, it could be speculated that the drift in case of the Teskcan Flexiforce A201 could also depend on the ratio of applied weight to maximum range. Sensor output reached the level of 97.3% from the stable value in 300 s and 98.5% in 600 s (Fergusson-Pell et al., 2000), but 90% in 450 s (Hollinger & Wanderley, 2006). However, this matter needs further investigation.

Sensor mounting

In order to ensure quick evaluations, it is advised to attach sensors on a glove rather than palmar skin. This approach will allow the researcher to perform calibrations before the arrival of the test subject. Obviously one glove size does not fit all. It has been suggested that for precise measurement the glove should be tailored for the test subject (Castro & Cliquet, 1997). However, using three different sizes (Lu et al., 2008) is a more practical approach. Moreover, glove thickness has been proven to reduce grip force (Wimer et al., 2010). Also, it can be extracted from Pylatiuk et al. (2006) that accurate positioning can be ensured by attaching sensors directly to skin. Moreover, Castro & Cliquet (1997) point out that people do not use gloves while performing everyday tasks. Lowe et al. (2007) noted that in industrial settings workers wear gloves and changing the normal work gloves for their 'force glove' is not a problem. In conclusion, one should critically analyse whether to attach sensors directly to palmar skin or to gloved hand.

The number of single sensors used in ergonomic assessment ranged from four (Radwin et al., 1992) or five (Pylatiuk) to 20 (Kargov et al., 2004; Lowe et al., 2006; Pylatiuk et al., 2006) sensors. There were 29 different sensor locations found in 19 settings (Fig. 1-A). However, Fellows & Freivalds (1991) and Pylatiuk et al. (2006)

used two different settings in one study. Therefore, these 19 settings were extracted from 17 different studies.

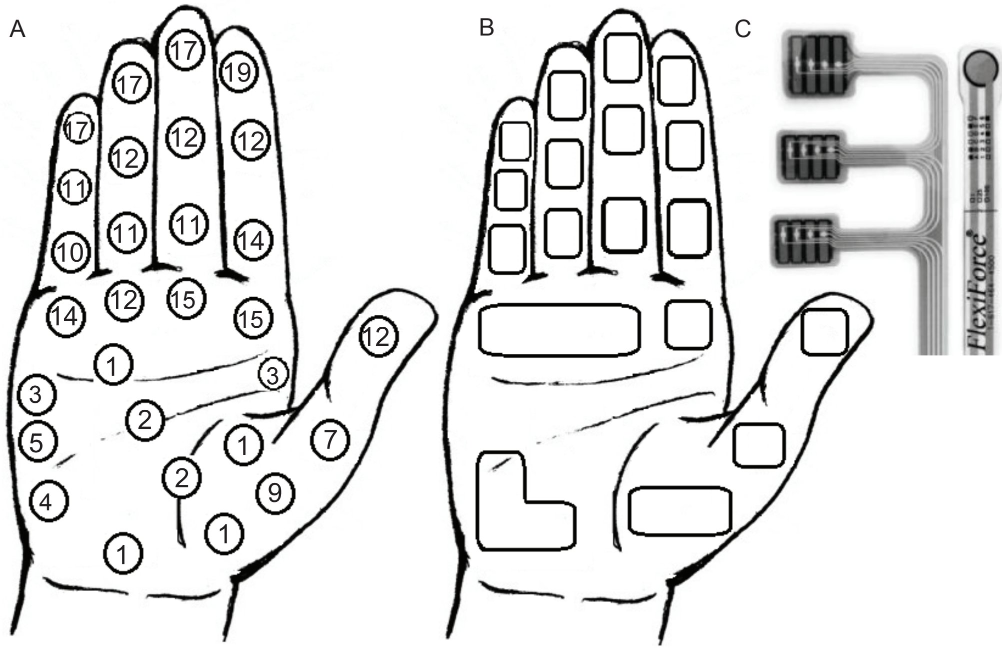

Figure 2. A) Distribution of the sensors, circles represent sensor locations in ergonomic studies, the numbers inside each circle represent the number of times the sensor location was used in 21 different settings; B) Locations of sensor regions of Tekscan 4256 (leads are now shown); C) Comparison of Tekscan sensors, three regions of 4256 (left) and Flexyforce A201 (right).

The number of sensors used in the study depends on the research object. The experiments of Radwin et al. (1992) and Pylatiuk et al. (2006) used four and five sensors, utilized pinch grip, and attached sensors only to distal phalanxes. A good example of a well-constructed measurement instrument is shown in a series studies by Kong (Kong & Freivalds, 2003; Kong & Lowe, 2005a; Kong & Lowe, 2005b; Lowe et al., 2006; Kong et al., 2007; Lowe et al., 2007a; Kong et al., 2008). The measurement instrument can be adjusted according to the researchers' needs by changing the number or locations of the sensors. Most studies by Kong et al. utilize 16 sensors (distal, medial, and proximal phalanxes and metacarpals of four fingers), settings with 12 or 20 sensors were used only once. Unique sensor locations are used in the studies of Hall (1997) and Björing et al. (2002) – only those two studies positioned sensors in the middle of the palm. Meanwhile, sensors were attached to the distal phalanx of the index finger in all measurement settings. The reason behind the relative unpopularity of the mid-palm area is mainly the object studied. In case of simple cylinder handle, the transverse metacarpal arch is not in contact with the handle, this is also demonstrated by Strasser & Bullinger (2007). However, in case of curved longitudinal contour, it may also be due to a connectivity issue. In order to attach a sensor in the middle of the palm area, the leads of the sensor must cross some other area on the subject's hand. It could restrict movement, impair dexterity, or interfere with other attached sensors which would conflict with the usability criteria.

Only a few studies reveal the reasoning behind chosen sensor locations. In the case of Fellows & Freivalds (1989; 1991), a pilot study was used. One had to grasp the tool handle after one's hand was dipped in finger paint. Areas of higher pressure were determined visually by change of paint coating on hand. Bishu et al. (1991) refers to an unpublished dissertation. Yun et al. (1992) refer to the above mentioned Fellows & Freivalds. Hall (1997) used the following criteria: 1) 'locations were expected to be exposed to pressure'; 2) locations had to coincide with a previous study about pain pressure threshold; 3) locations on the hand had to be evenly distributed.

Thenar region and the skinfold between the thumb and index finger are claimed to be the most sensitive areas of the hand (Fransson-Hall & Kilbom, 1993). However, according to the visualisation in Fig. 2-A, these areas tend to be underrepresented in ergonomic studies. There is no 'one and only' setting of sensor placement. If sensors (or sensor regions in case of sensor matrix) are attached to a glove, some of the hand surface remains uncovered. Thus, measured values tend to be underestimated (Kong & Lowe, 2005b).

CONCLUSIONS

Examples from scientific literature allow to conclude that state of the art pressure measurement sensors satisfy the criteria of usability. There are issues like sensor drift in curved surfaces that need further investigation as most ergonomic assessments deal with curved rather than plain surfaces. Attention should be paid to sensor selection. A trade-off between robustness, sensel density, sensor dimensions and wrinkling or induced accuracy loss is specific to handle geometry. A simple wet finger paint gripping test is most helpful for better understanding about hand-handle interface. Finally, interface pressure measurements are not yet an everyday tool for ergonomics research, but there is great potential for it to become one.

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