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Measurement of coupling forces at the power tool handle-hand interface

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ABSTRACT

This study explored a low-cost system for measurement of coupling forces imposed by the hand on a handle under static and dynamic conditions, and its feasibility for applications to hand-held power tools. The properties of thin-film, flexible and trim-able resistive sensors (FlexiForce) were explored in view of their applicability for measurements of the hand-handle interface forces. The sensors showed very good linearity, while considerable differences were evident in the sensitivity amongst different sensors. The appropriate locations of the sensors on the handle surface were subsequently determined on the basis of the hand-handle geometry and reported force distributions. The validity of the measurement system was investigated for measuring the hand grip and push forces with eight subjects grasping five different stationary instrumented handles (cylindrical: 32, 38 and 43 mm diameter; and elliptical: 32 × 38 and 38 × 44 mm) considering two different positions of the sensors on the handle. The validity of the measurement system was also investigated under vibration for the 38 and 43 mm diameter cylindrical handles. The results showed good linearity and repeatability of the sensors for all subjects and handles under static as well as vibration conditions, while the sensors' outputs differed for each handle. The feasibility of the measurement system was also examined for measurements of hand forces on a power chisel hammer handle. The evaluations were conducted with three subjects grasping the power chisel handle under stationary as well as vibrating conditions, and different combinations of hand grip, push and coupling forces. The measurements revealed very good correlations between the hand forces estimated from the FlexiForce sensors and the reference values for the stationary as well as the vibrating tool.

Relevance to industry: The measurement of hand-handle interface forces is vital for assessing the hand-transmitted vibration exposure and musculoskeletal loads. The low cost and flexible sensors, proposed in the study, could be conveniently applied to the curved surfaces of real power tool handles in the field to measure hand grip and push forces, and the forces exerted on the palm and the fingers. The most significant benefits of the sensors lie with its minimal cost and applicability to the real tool handles.

1. Introduction

Occupational exposure to hand-transmitted vibration (HTV) arising from operating hand-held power tools has been associated with an array of adverse health effects, including vascular, neurological and musculoskeletal disorders, collectively termed as hand-arm vibration syndrome (HAVS) and Raynaud's syndrome of occupational origin (Bovenzi et al., 1980; Malchaire et al., 1986; Bovenzi, 1998). The magnitude and frequency of HTV are strongly influenced by the coupling forces, grip type, handle geometry and other inter-individual factors. The HTV exposure is measured in terms of frequency-weighted acceleration of the vibrating tool handle using the method described in ISO 5349-1 (2001). However, the ISO 5349-1 guidelines do not account for the effects of coupling forces exerted at the hand-handle interface, although many studies

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have shown the importance of these forces in the transmission of vibration to the hand-arm system (Adewusi et al., 2010). The hand-handle interface coupling force, often considered as a combination of the grip and push forces, permits the flow of vibration energy from the tool into the hand (Aldien et al., 2006; ISO-15230, 2007). The coupling force thus directly affects the severity of vibration transmitted to the operator's hand and arm (Griffin, 1990; Hartung et al., 1993). Furthermore, an increase in grip force tends to compress the soft tissues of the hand and fingers, which may lead to reduced blood flow in the fingers and thus a greater risk of developing Raynaud's syndrome (Gurram et al., 1995).

A few recent studies have presented contradictory findings on the basis of the injury risks obtained from the ISO 5349-1 guidelines and epidemiological studies (Bovenzi, 2012; Griffin, 2012). Riedel (1995) suggested the use of a hand force coupling factor to account for the effect of the coupling force on the vibration dosage of the hand-arm system. The study showed insignificant differences between the acute effects of the grip and push forces, and thus recommended the sum of the two to derive the coupling force. A few studies have proposed additional weighting functions to account for strong effects of hand-handle interface forces on the exposure assessment (Kaulbars, 1995; Riedel, 1995; Kaulbars and Raffler, 2011).

Although the importance of considering the coupling forces on the quantification of the hand-arm vibration dosage has been widely recognized, the measurements of hand forces on vibrating tools have met only limited success. This is primarily attributed to the lack of definite relations between the static coupling forces and the HTV, and the lack of reliable measurement systems, particularly for field applications. Different designs of instrumented handles have been developed for measuring the hand forces with static as well as vibrating handles. Chadwick and Nicol (2001) proposed an instrumented handle comprising 6 segments of cantilevers with strain gauges attached at the fixed end. Wimer et al. (2009) explored the designs of 6, 8 and 10 segment instrumented handles similar to the design presented by Chadwick and Nicol (2001). These studies concluded that a six segment instrumented handle provided more accurate measurements of coupling forces under various gripping tasks. A similar handle design was proposed by McGorry (2001) for measurements of grip force and moments developed within the hand-handle interface. The instrumented handles employing piezoelectric load cells have been designed for measurements of the static and dynamic hand grip and push forces for studies on hand-arm biodynamic responses to vibration and for the assessment of anti-vibration gloves (Burström, 1997; Marcotte et al., 2005; Aldien et al., 2006; Dong et al., 2006; ISO-10819, 2013).

While the aforementioned instrumented handles have been widely used in the laboratory for measurement of hand forces with static as well as vibrating handles, their implementations to real tools in the field would involve considerable complexities. Furthermore, it has been reported that split instrumented handle designs affect the rigidity of the handle in an adverse manner. A number of studies have shown that instrumented handles employing either strain gauges or load cells are not always feasible for field usage with hand-held power tools since these require special fixtures (Yun et al., 1992; Chadwick and Nicol, 2001; McGorry, 2001; van der Kamp et al., 2001). Malinowska-Borowska et al. (2011) used a hydro-electric force meter along with an ALP pressure transducer and electronic manometer to measure coupling forces during logging operations. Calibrations results yielded highly favorable force measurement results (0–1.29% error) with forces in the range of 55–300 N; however, error exceeded 25% for smaller forces within the 0–55 N range. Since the current study employs a variety of low level forces alternate methods of measurement were explored.

In recent years, a few studies have explored the feasibility of thin film pressure sensing systems for the measurement of hand-handle coupling forces. These semiconducting, capacitive and resistive sensors exhibit adequate flexibility for applications to handles with different cross-sections and curved surfaces. The capacitive sensors consist of dielectric material separated by elastomeric layers and thus provide adequate flexibility and capacitance variations with the applied normal load. Resistive sensors, on the other hand, are designed with pressure-sensitive resistors encased between two thin polymer layers. Gurram et al. (1995) employed a 6×6 matrix of capacitive sensors on a cantilevered split handle for the measurement of grip pressure distribution under static as well as dynamic conditions. Subsequently, Welcome et al. (2004) and Aldien et al. (2005) used the capacitive sensing matrices for the acquisition of hand-handle contact and coupling forces under static conditions alone. The studies employed instrumented handles with load cells for the verification of the capacitive sensing matrix, and proposed empirical expressions relating grip, push, coupling and contact forces as a function of the handle size for 30, 40 and 48 mm handles. These studies have shown that the capacitive sensing matrix could provide accurate measurements of hand-handle grip, push and contact forces in a static laboratory setting under a controlled hand-arm posture. Deboli and Calvo (2009) used the similar sensing matrix for the determination of hand grip force imparted on a hand-held olive harvester. Young et al. (2010) used the capacitive sensing matrix to map distributed hand-handle interface forces under different gripping and pulling tasks.

Lemerle et al. (2008) further explored a capacitive pressure sensing matrix, developed by Novel GmbH, to measure the push and grip forces on power tools as a part of the comprehensive VIB-TOOL project, sponsored by the European Union. Although the VIB-TOOL project clearly demonstrated the reliability of the capacitive pressure sensing matrix for measurement of the hand-handle interface pressure distributions and coupling forces, the measurement system is not considered to be well-suited for field applications due to its very high cost. The capacitive sensors are also known to be relatively fragile and may incur damage and/or failure during field applications. Moreover, the validity of such sensors in capturing the dynamic hand-handle forces in frequency ranges of power tools has not yet been demonstrated.

Alternatively, a few studies have explored low cost force sensing resistors (FSR) for the measurement of hand-handle interface forces. Similar to the capacitive measurement system the FSR have also been applied in different matrix arrangements for the acquisition of interface force distributions. Komi et al. (2007) evaluated three different thin and flexible sensors for measurements of grip force imposed on a golf club. These included a resistive force sensing grid (model 9811, Tekscan), an arrangement of small-size FlexiForce sensors, developed by Tekscan Inc. (USA), and flexible Quantum tunneling composite (QTC) sensors developed by Peratech, Holdco Limited, UK. The study evaluated relative performance of the sensors under controlled laboratory conditions in terms of static accuracy, hysteresis, repeatability, drift errors, dynamic accuracy, shear loads and surface curvature effects. The study concluded better performance of the resistive force sensing grid and Flexiforce sensors compared to the QTC sensor, although all the sensors revealed high drift errors. The results of the study further showed reduced measurement sensitivities of both the resistive sensors compared to the static sensitivity of the QTC sensor. Furthermore, the sensitivity of all the three sensors decreased with their usage. In a recent study, Rossi et al. (2012) applied resistive pressure sensors (Tekscan 3200) to study the influence of handle diameter on the hand forces. The findings of the study were similar to those reported in Welcome et al. (2004),