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SHORT COMMUNICATION

Inertia artefacts and their effect on the parameterisation of keyboard reaction forces

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Reaction force measurements collected during typing on keyboard trays contain inertia artefacts due to dynamic movements of the supporting work surface. To evaluate the effect of these artefacts, vertical forces and accelerations were measured while nine volunteers touch-typed on a rigid desk and a compliant keyboard tray. Two signal processing methods were evaluated: 1) low pass filtering with 20 Hz cut-off; 2) inertial force cancellation by subtracting the accelerometer signal. High frequency artefacts in the force signal, present on both surfaces, were eliminated by low pass filtering. Low frequency artefacts, present only when subjects typed on the keyboard tray, were attenuated by subtracting the accelerometer signal. Attenuation of these artefacts altered the descriptive statistics of the force signal by as much as 7%. For field measurements of typing force, reduction of low frequency artefacts should be considered for making more accurate comparisons across groups using work surfaces with different compliances. Direct measures of physical risk factors in the workplace can improve understanding of the aetiology of musculoskeletal disorders. Findings from this study characterise inertia artefacts in typing force measures and provide a method for eliminating them. These artefacts can add variability to measures, masking possible differences between subject groups.

Keywords: exposure assessment tools; physical risk factors; work-related musculoskeletal disorders

1. Introduction

Typing forces may be a factor in the development of upper extremity musculoskeletal disorders. In a cross-sectional laboratory study, Feuerstein *et al.* (1997) observed that people with symptoms of musculoskeletal disorders of the upper extremity applied larger forces to the keyboard than people without symptoms. Similarly, Pascarelli and Kella (1993) reported that 26% of the injured computer users in their study had a forceful keying style. Marcus *et al.* (2002) observed higher incidence of symptoms for those who typed on a keyboard requiring higher activation forces. Moreover, Ripat *et al.* (2006) reported a decrease in symptom severity after an intervention to reduce keyboard activation forces. Since only one study measured actual force and did so only in the laboratory, there is a need to measure typing forces directly in the field in order to gain greater insight into the range of typing forces and the potential injury mechanisms associated with keying. However, as will be demonstrated, a challenge associated with taking measures in the field is the variability in the structure/stiffness of the typing work surface, which can substantially alter the quality and character of the measured typing forces.

Several laboratory studies of asymptomatic volunteers have quantified vertical keyboard reaction forces during typing using single axis force sensors located between the keyboard and the relatively stiff table top (Armstrong *et al.* 1994, Gerard *et al.* 1996, Gerard *et al.* 1999, Bufton *et al.* 2006, Dennerlein and Johnson, 2006, Won *et al.* 2008). In one study, typing forces were measured underneath the keyboard and at the fingertip, as measured with a custom-designed keycap force sensor (Martin *et al.* 1996). The force signal from underneath the keyboard contained high frequency artefacts, whereas the fingertip force signal did not. Since the desk was fairly stiff, Martin *et al.* (1996) concluded that the artefact was due to dynamics of the keyboard and its internal components (Martin *et al.* 1996, Rempel *et al.* 1994). These artefacts are often removed, without a major loss of the signal, by applying a high-order, low-pass filter with 20 Hz cut-off (Martin *et al.* 1996, Rempel *et al.* 1994, Dennerlein and Johnson, 2006, Won *et al.* 2008).

In the workplace, keyboards are often placed on adjustable keyboard trays cantilevered out from underneath a stiff desk in order to achieve proper keyboard height. These cantilevered supports are relatively compliant and therefore impulses, such as

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key strikes, can initiate vertical oscillations of the keyboard tray. Since the force sensors are located underneath the keyboard, they will be subjected to and record the inertial forces associated with the oscillation of the keyboard.

In fact, pilot studies have shown lower frequency artefacts (~ 5–15 Hz), which were not observed during typing on more rigid support surfaces such as desks. The frequencies of these artefacts are below the 20 Hz cut-off frequency used by many to remove the high frequency artefact. Reducing the filter cut-off to remove this lower frequency artefact becomes very challenging since the rate of key strikes, and hence tying forces, for a 60 word per min typist is around six strikes per second – the low pass filter would attenuate the typing forces of interest.

To remove this lower frequency artefact due to inertia forces, it is proposed to subtract the forces attributable to the vertical accelerations as measured with an accelerometer. While this is a simple approach, the effects of these inertia artefacts on descriptive statistics of the force signal for epidemiological studies are unknown. Therefore, this study aimed to characterise keyboard reaction force signals measured on two support surfaces – a rigid desk and a compliant keyboard tray; in order to evaluate how low-pass filtering and accelerometer-based inertia cancellation influences the measurement of typing forces.

2. Methods

2.1. *Experimental design*

Nine participants (three female, six male) completed a 90 s typing task on a full size QWERTY keyboard (KU-0225; Lenovo, Morrisville, NC, USA) supported by two work surfaces: 1) a standard cubical desk (Figure 1); 2) a more compliant keyboard tray (Details Keyboard Tray; SteelCase, Grand Rapids, MI, USA) mounted on the same desk (Figure 1). The order in which subjects completed each task was randomised. Subjects were instructed to ‘type the provided text while not resting your wrist on the edge of the keyboard or support surfaces’. Before each typing task, the experimenter tapped the keyboard on the space between the arrow keys and the navigation keys three times at a rate of 0.5 taps per second. This was done to generate oscillations in the force signal.

2.2. *Force and acceleration measurements*

A low profile force plate placed under the keyboard recorded the forces during the tapping and typing tasks. The keyboard force plate consisted of three load cells (ELW-D1–10L; Measurement Specialties, Hampton, VA, USA) secured to the bottom of a 480 mm × 180 mm × 6 mm aluminium and polycarbonate composite plate (Dibond, Fullerton, CA, USA). A Bridge and Strain Measurement Module (NI USB-9237; National Instruments, Austin, TX, USA) provided power and differential amplification for the load cell’s Wheatstone bridge circuits.

An accelerometer (356B41; PCB Piezotronics, Depew, NY, USA) with a frequency spectrum of 0.5–5000 Hz mounted to the surface of the force platform measured the vertical acceleration of the force plate. A Dynamic Signal Acquisition Module (NI-9233; National Instruments) provided power and first stage amplification for the accelerometer signal.

Figure 1. The workstation used for the typing experiments in the desk configuration on the left and the same workstation with the tray configuration on the right.

Both the force and acceleration signal modules were connected to a USB backplane (NI cDAQ-9172; National Instruments) and data were recorded to a personal computer using custom software (Labview V8.2; National Instruments). The signals from the three force sensors and the vertical component of the accelerometer were recorded at 200 samples per second.

2.3. *Data processing*

The stored digitised signals were processed through two sequential steps resulting in three representations of the force signal: unprocessed raw force (RAW); low-passed filtered force (LPF); filtered force with inertia cancellation (LIC). Digital processing was done with custom software (Labview V8.5; National Instruments). To obtain the LPF force signal, the RAW force signal was digitally filtered using a sixth order low pass Butterworth filter with a 20 Hz cut-off frequency; 20 Hz was chosen based on experience in completing laboratory force measurement studies (Dennerlein and Johnson 2006) and the fact that much of the force signal information during typing is below 20 Hz (Rempel *et al.* 1994). To obtain the LIC signal, the accelerometer signal was band-pass filtered using a sixth order low-pass Butterworth filter with a 1 Hz high pass and 20 Hz low pass cut-off frequency, then amplified and subtracted from the LPF force signal. The accelerometer gain was adjusted such that between the individual taps on the keyboard at 0.5 Hz, the resulting signal, after subtraction of the amplified accelerometer signal, was as close to 0 as possible. As very little acceleration was measured on the desk, the gain was set to 1.

2.4. *Data processing and analysis*

For each participant, support condition (desk and tray), and data signal (RAW, LPF, LIC and acceleration after filtering ACC), power spectral distribution and median power frequencies were calculated using an FFT Power Spectral Density module with a Hanning window. In total, 60 s (1200 samples) of data were analysed via the FFT. In addition, median (50th percentile) and peak (90th percentile) values for each signal were calculated.

To compare the descriptive statistics between the three representations of the force signal, a one-way repeated measures ANOVA modelled each descriptive statistic (dependent variable) as a function of the signal representation (independent variable) stratified by surface. If significance was found ($p < 0.05$) then Tukey HSD post-hoc analysis provided specific comparisons across the levels. A two-way repeated measures ANOVA model provided an additional comparison between the forces recorded on the two surfaces.

3. Results

High frequency artefacts can be seen in the force signal collected on both the desk and tray, while low frequency artefacts are apparent only on the tray (Figure 2). These low frequency artefacts persist for more than 1 s after contact is made with the keyboard.

Frequency analysis of the typing forces on the desk (left) and tray (right) shows the presence of both high and low frequency components (Figure 3). A high frequency component, between 40 to 50 Hz, is present when typing on both work surfaces. Above 5 Hz, there is a decay in the frequency content with the desk but no such decay with the tray. One notable difference is the prominent 9 Hz peak in the spectrum of the tray. Spectral analysis of the accelerometer signal (Figure 4) shows no peak spectral content from the desk, whereas the same prominent 9 Hz peak is present on the tray.

The effects of the signal processing steps are quite evident in both the time domain inspection of the single finger taps (Figure 5) and frequency domain analysis of the typing force signal (Figure 6). The power spectrums of the force signal after processing show a substantial reduction of the peak observed in the raw signal (Figure 3) between 40 and 50 Hz for both the desk and tray. For the tray there is also a reduction in the prominent 9 Hz peak. Inspection of

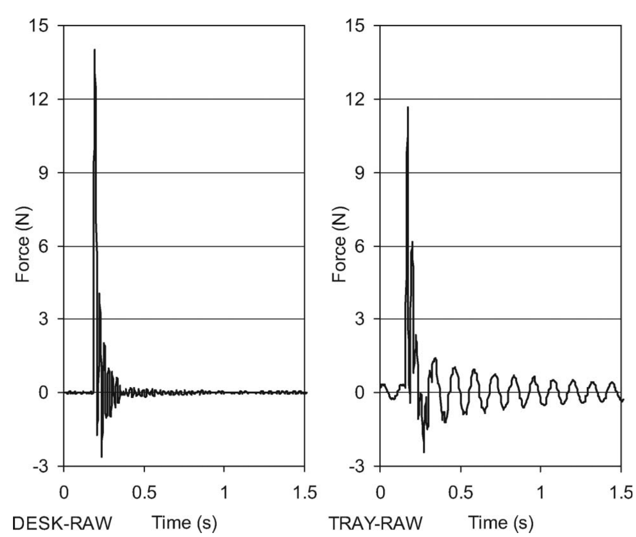

Figure 2. Unprocessed raw force (RAW) signal after a single tap on the desk (left) and tray (right) support surfaces. High frequency artefacts are evident for both surfaces, while low frequency artefacts are seen only for the tray surface.

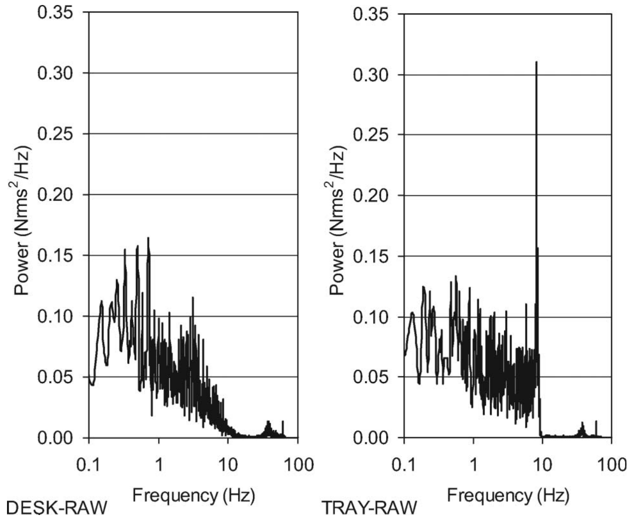

Figure 3. Spectral analysis of the unprocessed raw typing forces (RAW) for both the desk (left) and tray (right). The high frequency content is evident around 40–50 Hz for both the desk (left) and tray (right) surfaces. For the tray a spike can be seen at 9 Hz.

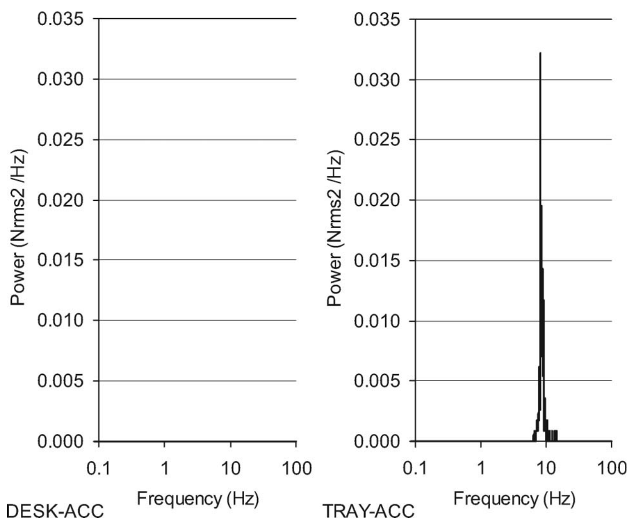

Figure 4. The power spectrum for the acceleration signal demonstrates the resonant frequency on the tray of approximately 9 Hz. There was no power in the acceleration signal on the desk. ACC = acceleration after filtering.

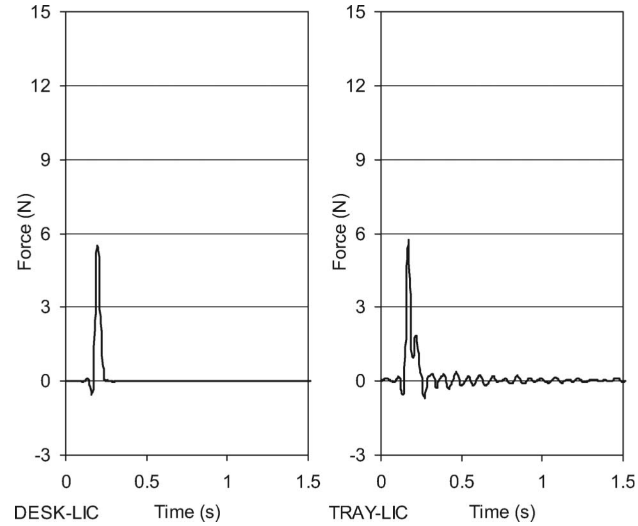

Figure 5. Filtered force with inertia cancellation (LIC) signal after a single tap on the desk (left) and tray (right) support surfaces. High frequency artefacts have been removed and low frequency artefacts are significantly attenuated on the tray surface.

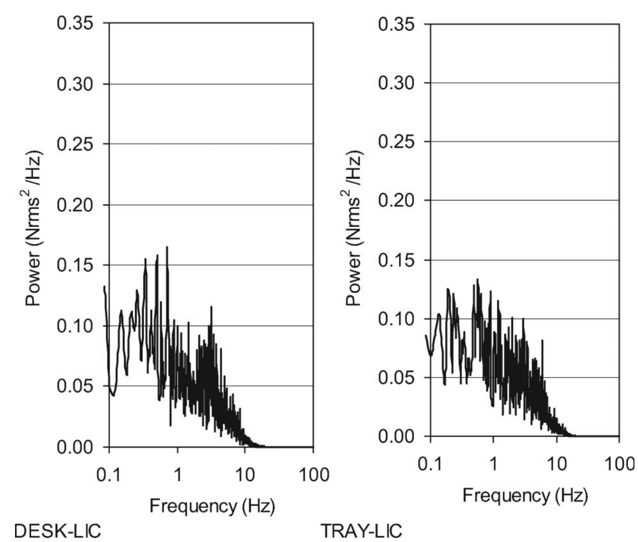

Figure 6. Spectral analysis of typing force data after the signal has been low-pass filtered for both the desk and tray and the inertia component subtracted out. The high frequency content is gone for both the desk (left) and tray (right) surfaces. For the tray the 9 Hz component is attenuated.

the processed force traces (Figure 5) shows that the high frequency components were removed for both the desk and tray and the decaying resonant signal is greatly attenuated for the tray.

Processing method had a significant effect on parameterisation of the force signal collected on the desk and tray and this effect was different for the two surfaces (Table 1). For the desk and the tray, low-pass filtering actually increased the 50th percentile metric by 5% and 3%, respectively. Low-pass filtering similarly decreased the 90th percentile metric by 7% and 4%, respectively. Inertia cancellation did not affect 50th or 90th percentile force values for typing on the desk; however, for the tray, the process reduced the 50th and 90th percentile metrics by 7% and 6%, respectively. Overall, the forces measures on the tray were 17% and

Table 1. Mean (SD) descriptive statistics for the different representations of the force signal and the two different support surfaces.

Metric	Surface	RAW	LPF	LIC	ANOVA *p*-value
50th (N)	DESK	0.57 (0.24)^{B}	0.59 (0.25)^{A}	0.59 (0.25)^{A}	0.002
50th (N)	TRAY	0.68 (0.21)^{A,B}	0.70 (0.22)^{A}	0.66 (0.24)^{B}	0.024
90th (N)	DESK	1.82 (0.28)^{A}	1.70 (0.28)^{B}	1.70 (0.28)^{B}	<0.001
90th (N)	TRAY	1.94 (0.24)^{A}	1.87 (0.24)^{B}	1.76 (0.24)^{C}	<0.001
MF (Hz)	DESK	3.84 (1.01)^{A}	2.80 (0.68)^{B}	2.80 (0.68)^{B}	<0.001
MF (Hz)	TRAY	4.72 (1.10)^{A}	4.09 (1.16)^{B}	2.93 (0.91)^{C}	<0.001

RAW = unprocessed raw force; LPF = low-pass filtered force; LIC = filtered force with inertial cancellation; MF = median power frequency.
Note: ANOVA *p*-values indicate overall effect, superscripts indicate pair-wise comparison differences. Values with the same superscript are not significantly different.

7% higher for the 50th and 90th percentile metrics respectively when compared to the forces measured on the desk (two-way ANOVA, $p < 0.001$). Median power frequency values were also different across surfaces (two-way ANOVA, $p < 0.001$).

4. Discussion

The present study aimed to characterise keyboard reaction force signals measured across two common support surfaces with varying stiffness and to evaluate two simple signal processing methods to remove force artefacts due to vibrations and oscillations of the keyboard components and support surface. The results demonstrated that low-pass filtering successfully eliminates high frequency artefacts while inertia forces, due to accelerating the mass of the keyboard, can be removed by subtracting a scaled version of the vertical acceleration parallel to the axis of the keyboard force sensor. In addition, there appears to be different force characteristics between typing on a desk and a keyboard.

High frequency artefacts are present on both the sturdy desk and keyboard tray, which implies that they are inherent in the keyboard itself. Martin *et al*. (1996) also attributes such keyboard force artefacts to these components. The frequency domain analysis (Figure 3) demonstrates that most of the signal forces are well below 20 Hz. Hence, a low-pass filter is sufficient to eliminate much of the artefact produced when typing on reasonably stiff surfaces, as the artefacts have a higher frequency component than the typing force.

When typing on a keyboard tray, however, low frequency inertia artefacts were introduced. As described in section 1, the force sensors underneath the keyboard also measure the inertia forces needed to accelerate the mass of the keyboard up and down with the movement of the tray. Since the cantilever design of most keyboard trays is relatively compliant, the impact of the fingertips on the keyboard causes the system to oscillate. These accelerations are parallel with the load cells and therefore result in artefacts in the recorded force signal. Measuring the accelerations makes it possible to quantify these inertia components with a simple gain (the mass of the keyboard). The results demonstrate that these artefacts can easily be removed by subtracting the inertia force from the load sensor signals.

The low frequency inertia artefacts seen only during typing on the compliant tray significantly alter both 50th and 90th percentile values. While the effect is not very large, the 7% difference seen is nearly one-third of the 20% difference that Feuerstein *et al*. (1997) reported in typing forces between subjects with musculoskeletal complaints and asymptomatic controls. Since inertia artefacts are only present during typing on compliant support surfaces, comparing data across subjects that use different support surfaces will add a systematic bias to force calculations and therefore make detecting differences between groups more difficult.

The results also suggest that the forces measured while typing on a keyboard tray and on a desk are different. Even after all the signal processing to remove the known artefacts, the forces on the tray were higher than the desk. In addition, the shapes of the power spectrums are qualitatively different between the two surfaces and the desk had lower median frequency values quantifying this different shape. These data are somewhat suggestive that typing on a keyboard tray may be a different experience than typing on a desk surface. However, exploring the differences in typing forces or the motor control behind such differences is beyond the scope of this current work and conclusions made from this study are limited by protocols. Nonetheless, these data suggest that care needs to be taken when comparing forces between the two different surfaces.

In conclusion, high frequency artefacts observed in keyboard force measurements during typing can be effectively removed by low-pass filtering. Measuring forces on keyboard trays provides a challenge due to their compliant nature. However, with the use of an accelerometer much of the artefact due to accelerating the keyboard mass up and down can be effectively removed by measuring this acceleration and subtracting the associated inertia load from the force measurements. These factors can have implications for any epidemiological study when comparing forces across a cohort of computer users.

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