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Effect of ergonomic Armrest® forearm support on wrist posture related to carpal tunnel pressure during computer mouse work

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ABSTRACT

Objective: We validated the effect of moveable arm support (Armrest®) on wrist posture during three standardized tasks.
Background: The use of the computer mouse has been increasing over the years and it has been identified as one of the occupational activities related to carpal tunnel syndrome (CTS). The main mechanism for CTS is carpal tunnel pressure (CTP) that could be estimated from the wrist posture.
Method: Using an electronic goniometer, we assessed wrist extension/flexion and ulnar-radial flexion in 15 participants (age: 34.8 [8.7] years) and calculated the time the wrist posture was outside the threshold values previously related to CTP. Specifically, we estimated time when wrist posture yielded >25 mmHg of CTP: wrist extension >32.7°; wrist flexion < −48.6°; wrist ulnar flexion >14.5°; and wrist radial flexion < −21.8°.
Results: Average wrist extension/flexion tends to be 13.4° lower ($p = 0.063$), while radial-ulnar flexion was 13.2° lower ($p = 0.025$) when Armrest® forearm support was used in comparison to fixed forearm support. Furthermore, the time spent outside the threshold wrist extension was 25.8% ($p = 0.018$) lower and ulnar flexion was 37.2% ($p = 0.017$) lower when using Armrest® compared to a fixed forearm support. Results were independent from tasks.
Conclusion: Armrest® diminished the time spent outside the threshold values related to 25 mmHg of CTP indicative of CTS.
Application: A moveable arm support is a simple and effective way to increase occupational health during computer mouse work.

1. Introduction

During working hours at computer workstations, keyboard and mouse have been used over the last 30 years to transfer information into a digital medium and work with it. This use has been increasing over the years both among the working population and among non-professional users. With the number of users increasing, the time when the mouse is used as an input device has also demonstrably increased, which has created new problems in today's workplaces. Nowadays, pointing devices (i.e., computer mouse, trackballs, etc.) are found in every office environment (Fagarasanu & Kumar, 2003). Current computer workstation design requires manual control of the mouse, typically exceedingly, as much as three times as long as keyboard usage (Feathers et al., 2013; Odell and Johnson, 2015). For example, office workers are interacting with computer workstations 160 min daily during the 6.5 h of total daily computer time, including breaks (Eijckelhof et al., 2014).

With regard to occupational activities, one of the most common pathological conditions associated with this activity are overload syndromes, the pathogenesis of which is usually associated with the repetition of the same movements. Among all overexertion syndromes, carpal tunnel syndrome (CTS) is particularly relevant (Katz and Simmons, 2002; Padua et al., 2016; Patterson and Simmons, 2002). One of the causative factors for carpal tunnel syndrome is persistently elevated carpal tunnel pressure (David Rempel et al., 1999) both in patients with CTS and in healthy persons when the wrist deviates from the neutral position (Gelberman et al., 1981; Okutsu et al., 1989; Rojviroj et al., 1990; Werner and Armstrong, 1997). Since the time that a mouse was used as an input device several studies have suggested that the risk of CTS increases with the number of hours of computer use (Andersen et al., 2003; Clarke Stevens et al., 2001; Franco et al., 1992; Franzblau

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et al., 1993; Jacobs et al., 2009; Karlqvist et al., 1994).

Reducing musculoskeletal disorders associated with the computer mouse use induced ergonomic solutions for traditional computer mouses, either by redesigning the mouse itself or adding forearm supports, both aiming to reduce carpal tunnel pressure. The slanted or vertical mouse should be favored over a standard mouse due to its more natural wrist posture (Gaudez and Cail, 2017). There were no important differences found in wrist posture or carpal tunnel pressure between the three computer mice tested but they found an increase in carpal tunnel pressure when using the mouse as opposed to resting the hand on the mouse (Peter J. Keir et al., 1999). Even more, when comparing a standard horizontal with a vertical mouse, greater efficiency and effectiveness were found when the horizontal mouse was used; specifically, the discomfort, effort, and ease of use across the different tasks favored the horizontal mouse (Lourenço et al., 2017). The results suggest that designing hybrid configurations may lead to a better compromise. It seems that carpal tunnel pressure increases when using the computer mouse, regardless of its type and hand support, while the vertical mouse reduces ulnar deviation, and a gel mouse pad and gliding palm support decrease wrist extension (Schmid et al., 2015). Promising results were found for an Ergorest® robotic forearm support that decreases wrist extension but only if used in both hands (Lintula et al., 2001). However, it is unknown during which tasks (keyboard typing or mouse work) this effect was found.

These studies suggest using non-invasive test methods (usually electromyography or goniometry) with the threshold criteria of recommended wrist carpal pressure when comparing different computer mouse modalities and/or ergonomic designs where two longitudinal studies used invasive measurement of carpal tunnel pressure (Peter J. Keir et al., 1999; Schmid et al., 2015). The overall results indicated that there is no mouse modality or ergonomic solution adequate to reduce either direct measure of carpal tunnel pressure or indirect measure of wrist angles when working with the computer mouse. Therefore, we proposed a new ergonomic solution – Ergonomic Armrest® (Armrest®; Mouzen d.o.o., Slovenia) forearm support (Fig. 1). The innovative nature of its design is in its almost frictionless translation of the supported forearm in both directions.

The Armrest® forearm support was designed for efficient and healthier computer mouse work on selected CTS-related health parameters. It assures two-dimensional smooth translation of the forearm (single or both) support in the work with computer input devices (keyboard, joystick, and mouse) and should serve as an ergonomic aid in the prevention of CTS or discomfort. For non-invasive studies an ergonomic guideline for the position of the wrist posture at the workplace exists (Peter J. Keir et al., 2007). The guidelines reported threshold wrist angles in both directions (flexion/extension and ulnar-radial flexion). Although they proposed two threshold values, for carpal tunnel pressures of 25 and 30 mmHg, we should consider 25 mmHg as the threshold limit for carpal tunnel pressure, since at 30 mmHg pathological deformations already occur: the swelling and demyelination of the nerve (Lundborg et al., 1983; David Rempel et al., 1999).

Therefore, the aim of this study is to evaluate the relative time spent above threshold angles in wrist extension/flexion and ulnar-radial extension/flexion during standardized horizontal computer mouse work with Armrest® and without it. Furthermore, we evaluated the computer task efficiency and user experience.

2. Material and methods

2.1. Participants

The study included 15 male and female participants (47% female) aged between 30 and 50 years (age: 34.8 [8.7] years; body height: 1.73 [7.2] m; mass: 67.3 [9.1] kg; body mass index: 22.2 [1.3] kg/m2) who regularly use a computer mouse at their work. None of the participants had a past or current problem with carpal tunnel syndrome. All the participants were right-handed. They were informed about the experimental procedures before giving their consent, and they had no previous experience with the use of Armrest® forearm support.

2.2. Research design

Each participant had a familiarization trial to experience standardized work tasks and testing procedures before the assessments. Later, each participant came to the laboratory on two separate days (24 or 48 h in between) and performed three standardized computer tasks (30 min) on a laptop computer (Lenovo T440p) with a computer mouse (Canyon CNE-CMS2) with or without Armrest® forearm support (in a random order). Participants had 3 min of rest between work tasks and were asked to relax their forearms on the table. All instructions, sensor mounting, and computer tasks were the same for both conditions. We choose 30-min periods due to the fact that wrist posture does not change during longer computer tasks (David M. Rempel et al., 2008) and it was assumed that the 30-min task duration would be representative during prolonged mouse tasks.

2.3. Computer mouse work tasks

The work tasks were performed on a 14″ laptop with a resolution of 1366 × 768 pixels (height: 17.5 cm and width 31 cm). The distance between the participant's eyes and the screen was set at approximately 50 cm, with the upper body back post.

Retyping numbers (20 min): Participants retyped 4-digit numbers between two sheets within the same Excel file. Namely, we wrote random numbers in random rows in the first sheet with at least 20 blank rows between two numbers. Once the participants remembered the number and the row/column in the first sheet, they had to rewrite it in the same row and column in the target sheet. However, the target sheet was the thirtieth sheet in the same Excel file, so the participants needed to scroll not only vertically (13 cm) but also move the mouse horizontally (27 cm) for each retyped number. We recorded the number of retyped numbers and the number of errors, either the wrong number or

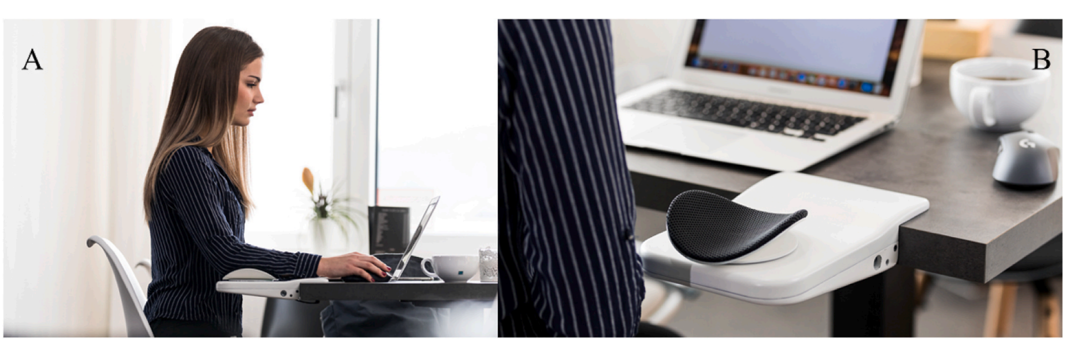

Fig. 1. Ergonomic Armrest® forearm support (A and B).

the wrong position.

Shooting balloons (5 min): Participants tried to hit as many balloons as possible, with the balloons changing in their diameter constantly from their appearance at zero diameter to the maximal diameter and disappearing back to zero. Balloons appeared in a window, sized 18 cm (width) and 12 cm (height). We recorded the number of balloons hit and the number of failed attempts.

Fitts's Law test (5 min): Fitts's Law (1954) is a widely accepted conceptual model within which it is possible to evaluate human–computer interaction (MacKenzie, 1992) and is often used in ergonomic analysis of the working place (Quemelo and Vieira, 2013). In a typical Fitts's Law procedure, the speed and accuracy of a movement from a starting point to a target (which varies in width) and distance or amplitude are measured. Vertical bars appeared in a window sized 29 cm (width) and 15 cm (height). It is to be expected that the different configuration of the input device (with and without Armrest®) would involve different patterns of wrist angles used in positioning actions. We recorded the relative number of errors and the positioning time of the mouse.

2.4. Measurement methods

We mounted two unidimensional goniometers (SG110, Biometrics Ltd., UK) on the forearm and hand to assess wrist angular movements in the directions of flexion/extension and ulnar-radial flexion (Fig. 2A). Goniometers were acquired at a sampling frequency of 1.5 kHz with a wireless data acquisition system (TeleMyo 2400, Noraxon, USA). Both goniometers were calibrated to zero before mounting. Then both goniometers were glued together to detect wrist movements in two directions. The first goniometer assessed wrist flexion/extension and was attached proximally and distally from the wrist. The second goniometer assessed ulnar-radial flexion of the wrist and was attached to be aligned with the hand direction, proximally in the direction of midline from the elbow to the wrist and distally in the direction of the mid-wrist to the line of the middle finger. We used medical tape to attach goniometers to the skin. Data acquisition was done continuously for the time of the experiment (36 min) and break points were used to delimit each task duration for further analysis (see Fig. 3).

Immediately after each assessment participants completed a User Experience Questionnaire (UEQ).

2.5. Sitting position and forearm support

We used an adjustable standard office chair to assure the same sitting position in performing the tasks with Armrest® forearm support or without it. The height of the chair was adjusted so that the participants' feet were positioned flat on the floor with their knees at 90°, their elbows resting on the table in 90° flexion and the back was rested on the chair backrest. The main difference between both conditions was in forearm support. Specifically, we acquired a prototype forearm support Ergonomic armrest® to assure forearm support with a movable pad to allow smooth forearm movement in all directions (Fig. 1). When this support was not used, the elbow rested on a fixed chair forearm support.

2.6. Data processing

The goniometer data were transferred in Matlab (Matlab R2017b, Mathworks, USA) and filtered using a zero-phase digital Butterworth low pass 5th order filter (function *filtfilt*) with a 75 Hz cut-off frequency. Then we analyzed goniometer records for each work task separately as well as for pooled tasks. From each record we calculated the average angle and the time the wrist angle was higher than the threshold values determined by Keir et al. (2007), which in 75% of the population equaled 25 mmHg pressure in the carpal tunnel: wrist extension $>32.7^\circ$; wrist flexion $< -48.6^\circ$; wrist ulnar flexion $>14.5^\circ$; and wrist radial flexion $< -21.8^\circ$.

2.7. Statistics

All data are presented as means with standard deviations. Due to low N and non-normal distribution we used the two-tailed Wilcoxon sign range test for pairwise comparisons between both conditions, with and without Armrest® forearm support. All statistical decisions were done at $\alpha < 0.05$; however, due to low health risk we also took into consideration $\alpha < 0.1$ for reporting a trend towards significance.

3. Results

In Table 1 we can see differences in wrist angles when participants used Armrest® forearm support. Pooled analysis of all three tasks revealed that the wrist extension was above critical angle only 1.5% of the tasks' time when Armrest® forearm support was used and that is 25.8% ($p = 0.018$) lower in comparison to fixed forearm support. Similarly, ulnar flexion was above critical angle only 19.5% of the tasks' time when Armrest® forearm support was used, being 37.2% ($p = 0.017$) lower compared to fixed forearm support. The average wrist posture variation was 13.4 lower ($p = 0.063$) and the average ulnar-radial flexion variation was 13.2 lower ($p = 0.025$) when Armrest® forearm support was used. When observing results from each specific task, we found similar results as in pooled data of all three tasks.

Table 2 presents the efficiency of performing all three work tasks. In Table 1 we could see differences in wrist angles when participants used Armrest® forearm support and when they did not. Pooled analysis of all three tasks revealed that the wrist extension was above critical angle

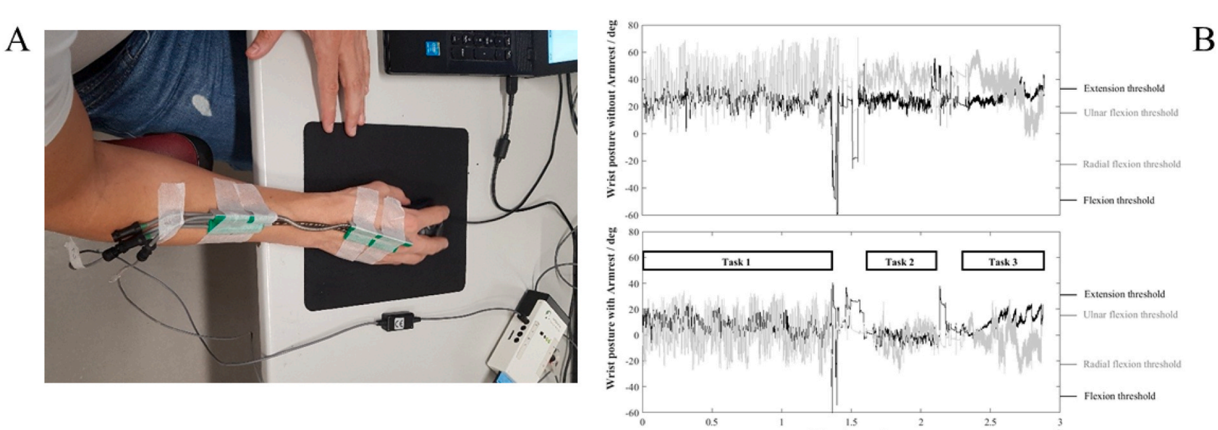

Fig. 2. Mounting of two unidimensional goniometers to assess wrist flexion/extension and radial-ulnar flexion (A). A typical trace of goniometers (B).

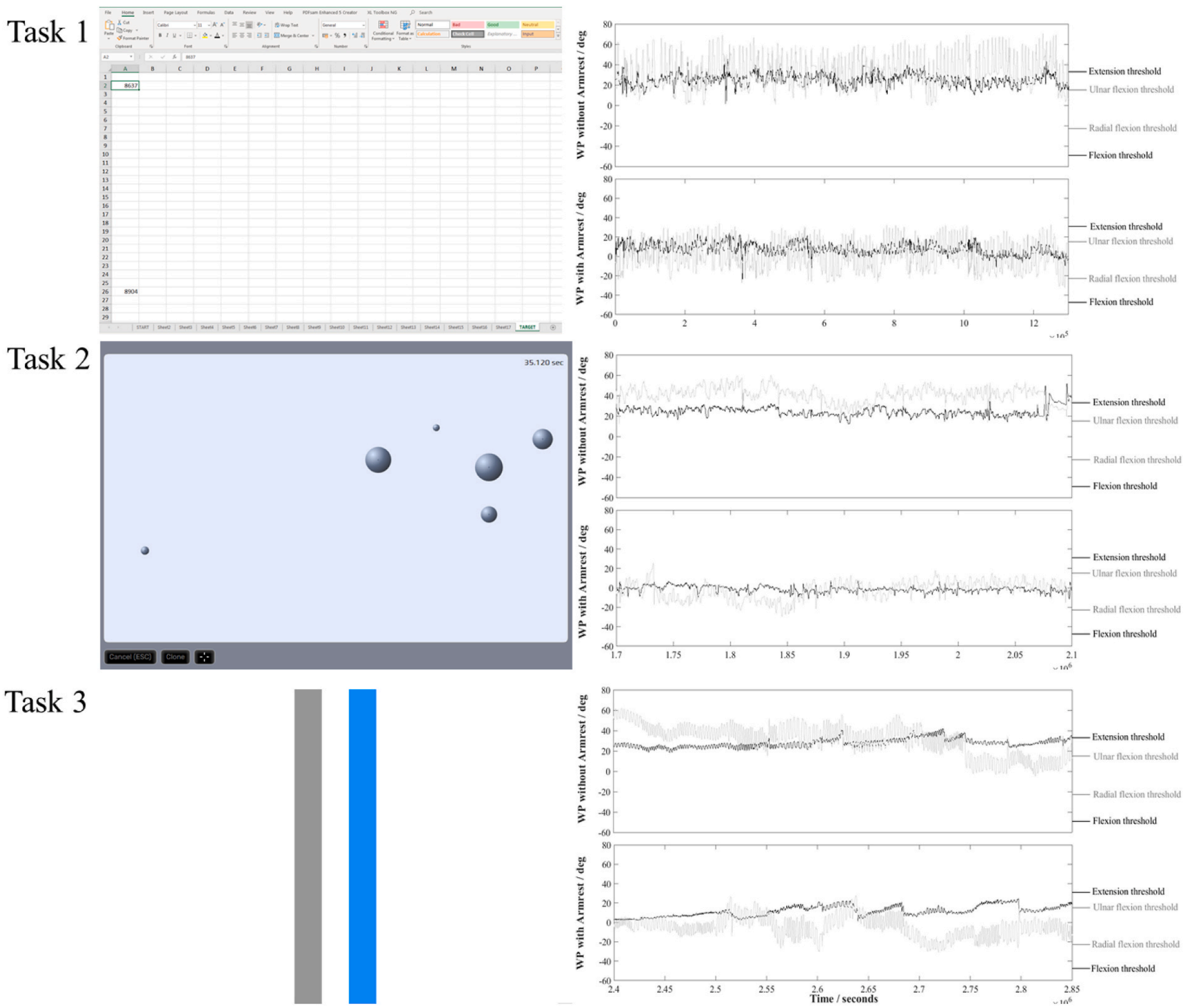

Fig. 3. A graphical overview of all three tasks width detailed representation of wrist posture (WP) during each task with and without Armrest® support.

only 1.5% of the tasks' time when Armrest® forearm support was used and that is 25.8% ($p = 0.018$) lower in comparison to the figure for fixed forearm support. Similarly, ulnar flexion was above critical angle only 19.5% of the tasks' time when Armrest® forearm support was used, 37.2% ($p = 0.017$) lower compared to fixed forearm support. The average variation was 13.4° lower ($p = 0.063$) and the average ulnar-radial flexion variation was 13.2° lower ($p = 0.025$) when Armrest® forearm support was used in comparison to the values for fixed forearm support. When observing results from each specific task, we found similar results as in the pooled data of all three tasks.

The results indicated that tasks 1 and 2 were performed with the same efficiency with either forearm support, while in task 3, aiming time increased by 4.1% ($p = 0.039$) when Armrest® forearm support was used.

After the Armrest® forearm support was used, the UEQ was filled, and from Fig. 4A we can see mainly positive user experience results: 20 of 26 items, where 14 of 26 items could be classified as neutral experiences (−0.8 to 0.8), and 12 of 26 items are classified as positive experiences (>0.8). Participants believed that Armrest® was more enjoyable, interesting, easy, supportive, efficient, predictable, and pleasant to use with a computer mouse. However, participants also classified their experiences with Armrest® forearm support as slow, dull, and demotivating. In Fig. 4B we pooled UEQ items in logical categories and found that attractiveness, perspicuity, and dependability could be classified as positive experiences while efficiency, stimulation, and novelty as rather neutral experiences.

4. Discussion

We found reduced wrist extension and ulnar flexion time above the angles critical for development of carpal tunnel syndrome in both wrist directions when moveable hand support was used in comparison to no support. Furthermore, we found lower average variation of ulnar/radial wrist flexion and a trend toward lower average variation in wrist extension/flexion direction. It seems that the results are independent of the tasks performed. Although most of the tasks' performance indicators remained unchanged, the aiming time in Fitts's Law test were increased by only 4% when moveable Armrest® hand support was used.

Similar findings were obtained in a study by Lintula (Lintula et al., 2001). Specifically, they evaluated the use of a similar moveable hand support (Ergorest®) that allows three-dimensional movement through an adjustable lever arm in combination with a supporting pad just below the elbow. They found much lower beneficial effects with Ergorest® support during computer mouse tasks, which were only 3.7% lower decrease in average wrist extension, in comparison to fixed support, while Armrest® decreased wrist extension by 13.4%. Their research design also allowed for long-term effects and they did not report any further beneficial effects on wrist angles.

Other studies optimised computer mouse set-up rather than changing hand support. Keir (Peter J. Keir et al., 1999) tested three different mouse models and found no difference in wrist extension angle (wrist extension angle was 25–30° during tasks and 23–28° during rest) or ulnar-radial flexion. Data obtained from similar studies (Chen and

Table 1
Differences between working with the use of Armrest® forearm support and without it (fixed forearm support) in time spent above threshold wrist positions for: flexion/extension and radial-ulnar flexion directions with an average angle in both directions.

	With fixed forearm support	With Armrest® forearm support	p-value
N	15	15	
Task 1: Retyping numbers			
Extension >32.7°/%	23.5 (35.2)	0.3 (0.7)	0.018*
Flexion < −48.6°/%	0.0 (0.0)	0.0 (0.0)	0.317
Average extension/flexion/°	26.8 (7.8)	15.0 (13.9)	0.063T
Ulnar flexion >14.5°/%	48.4 (38.4)	27.5 (28.6)	0.059T
Radial flexion < −21.8°/%	0.0 (0.1)	0.4 (1.1)	0.686
Average ulnar-radial flexion/°	15.7 (14.0)	7.3 (12.2)	0.038*
Task 2: Shooting balloons			
Extension >32.7°/%	26.0 (35.2)	0.9 (1.0)	0.018*
Flexion < −48.6°/%	0.0 (0.0)	0.1 (0.3)	0.317
Average extension/flexion/°	29.2 (7.2)	18.0 (10.9)	0.028*
Ulnar flexion >14.5°/%	60.3 (43.7)	23.8 (38.6)	0.038*
Radial flexion < −21.8°/%	0.0 (0.0)	0.2 (0.6)	0.180
Average ulnar-radial flexion/°	20.4 (16.3)	8.8 (12.8)	0.036*
Task 3: Fitts's Law test			
Extension >32.7°/%	43.7 (38.6)	6.7 (8.8)	0.028*
Flexion < −48.6°/%	0.0 (0.0)	0.0 (0.0)	>0.999
Average extension/flexion/°	31.2 (8.3)	21.5 (7.7)	0.063T
Ulnar flexion >14.5°/%	44.8 (36.1)	19.5 (34.6)	0.007*
Radial flexion < −21.8°/%	0.7 (1.8)	1.2 (2.2)	0.715
Average ulnar-radial flexion/°	16.1 (11.8)	4.2 (14.2)	0.012*
Pooled tasks			
Extension >32.7°/%	27.3 (33.2)	1.5 (1.6)	0.018*
Flexion < −48.6°/%	0.0 (0.0)	0.0 (0.0)	0.180
Average extension/flexion/°	30.0 (7.4)	16.6 (11.9)	0.063T
Ulnar flexion >14.5°/%	56.7 (35.4)	19.5 (13.4)	0.017*
Radial flexion < −21.8°/%	0.1 (0.2)	0.4 (1.1)	0.249
Average ulnar-radial flexion/°	19.1 (13.4)	5.9 (11.3)	0.025*

T … a trend towards significance at $p < 0.1$; * … statistically significant at $p < 0.05$.

Leung, 2007; Feathers et al., 2013; Gaudez and Cail, 2017; Lourenço et al., 2017) showed minor differences between the tested mouse models in the hand posture during task performance, and expressed the need for some kind of arm support that would allow easier, more efficient and more comfortable use during daily work tasks.

Full pronated forearm during computer mouse work affects carpal tunnel pressure (David M. Rempel et al., 2008; Werner and Armstrong, 1997). It was also found that excessive flexion/extension and ulnar-radial extension could increase carpal tunnel pressure to the limits where it is indicative of CTS (Peter J. Keir et al., 2007). So, there is a substantial need to develop and validate approaches to assure healthy work with a computer. One of these is the forearm support, be it fixed (Cook et al., 2004a, 2004b; Gonçalves et al., 2017; David M. Rempel et al., 2008) or moveable, as it was in our study and in the study of Lintula (Lintula et al., 2001). The effects of forearm support on musculoskeletal disorders (wrist posture deviations) and upper body complaints, and the efficiency of newly developed solutions were mixed.

Table 2
Efficiency in performing work tasks with Armrest® forearm support and without it (fixed forearm support).

	With fixed forearm support	With Armrest® forearm support	p-value
N	15	15	
Task 1: Retyping numbers			
Number of retyped numbers	53.8 (14.8)	51.6 (10.0)	0.472
Number of errors	2.1 (2.4)	2.0 (1.7)	0.820
Task 2: Shooting balloons			
Number of hits	276 (81)	276 (69)	0.997
Number of misses	69 (38)	77 (36)	0.395
Aiming time/sec	1.16 (0.42)	1.15 (0.37)	0.831
Task 3: Fitts law test			
Aiming time/sec	0.761 (0.92)	0.792 (0.99)	0.039*
Error rate/%	3.09 (2.49)	2.56 (1.88)	0.274

* … statistically significant at $p < 0.05$.

In a study by Rempel (D. M. Rempel et al., 2006) positive effects of a forearm support on upper body disorders as well as on pain scores of the upper extremities were found. Similarly, reduced muscle activation of the upper body region was shown when forearm support was used (Cook et al, 2004a, 2004b; Gonçalves et al., 2017; Nag et al., 2009), but not when hand pads (Onyebeke et al., 2014), a moveable support (Lintula et al., 2001), or larger but still fixed ergonomic supports were used (D. M. Rempel et al., 2006).

We used a non-invasive indirect approach to validate the effectiveness of a moveable arm support; however, we followed the ergonomic guideline for wrist posture based on carpal tunnel pressure thresholds (Peter J. Keir et al., 2007). The guideline was developed by invasive carpal tunnel pressure assessment with a saline-filled catheter inserted percutaneously into the carpal tunnel. The wrist posture was modulated in two directions: flexion/extension and ulnar-radial flexion. The critical thresholds were defined at 25 mmHg, as compression pressures as low as 20 mmHg can already decrease blood flow inside the nerve, while pressures above 30 mmHg can reduce nutrient transport down the nerve axon (Lundborg et al., 1983; Rydevik et al., 1981). Specifically, brief 30 mmHg compression can cause vascular permeability and may lead to a persistent edema in the nerve (Lundborg et al., 1983). These studies support a pressure threshold for nerve injury at or just below 30 mmHg; however, they are considered as minimal protection from nerve injury (David Rempel et al., 1999). Carpal tunnel pressure is influenced by wrist posture (P. J. Keir et al., 1997, 1998a; Peter J. Keir et al., 2007; Werner and Armstrong, 1997), forearm posture (D. Rempel et al., 1997; Werner and Armstrong, 1997), finger posture (P. J. Keir et al., 1998b), and fingertip force (P. J. Keir et al., 1998b; D. Rempel et al., 1997). Carpal tunnel pressure further increases with forearm pronation or supination (D. Rempel et al., 1998; Werner and Armstrong, 1997), with finger extension or flexion (Cobb et al., 1995; P. J. Keir et al., 1998a), and with wrist deviation from neutral (P. J. Keir et al., 1998a; Weiss et al., 1995).

The limitation of our study is in the assessment of only wrist manipulation, without assessing forearm and finger posture. We focused on specific standardized tasks; however, for future research, we propose other standardized tasks to evaluate the efficacy of the armrest in other aspects of mouse use. Furthermore, we used a medium-sized computer mouse (depth: 10.9 cm; height: 3.8 cm; width: 6.7 cm), which allowed for an easier wrist and finger strategy of mouse manipulation. This is not possible for larger mice (as well as for medium-sized mice in small hands), and the positive effects of the Armrest would be even better due to more elbow and shoulder strategy of mouse movement. However, there is no study reporting the effects of different mouse sizes on the biomechanics of mouse manipulation.

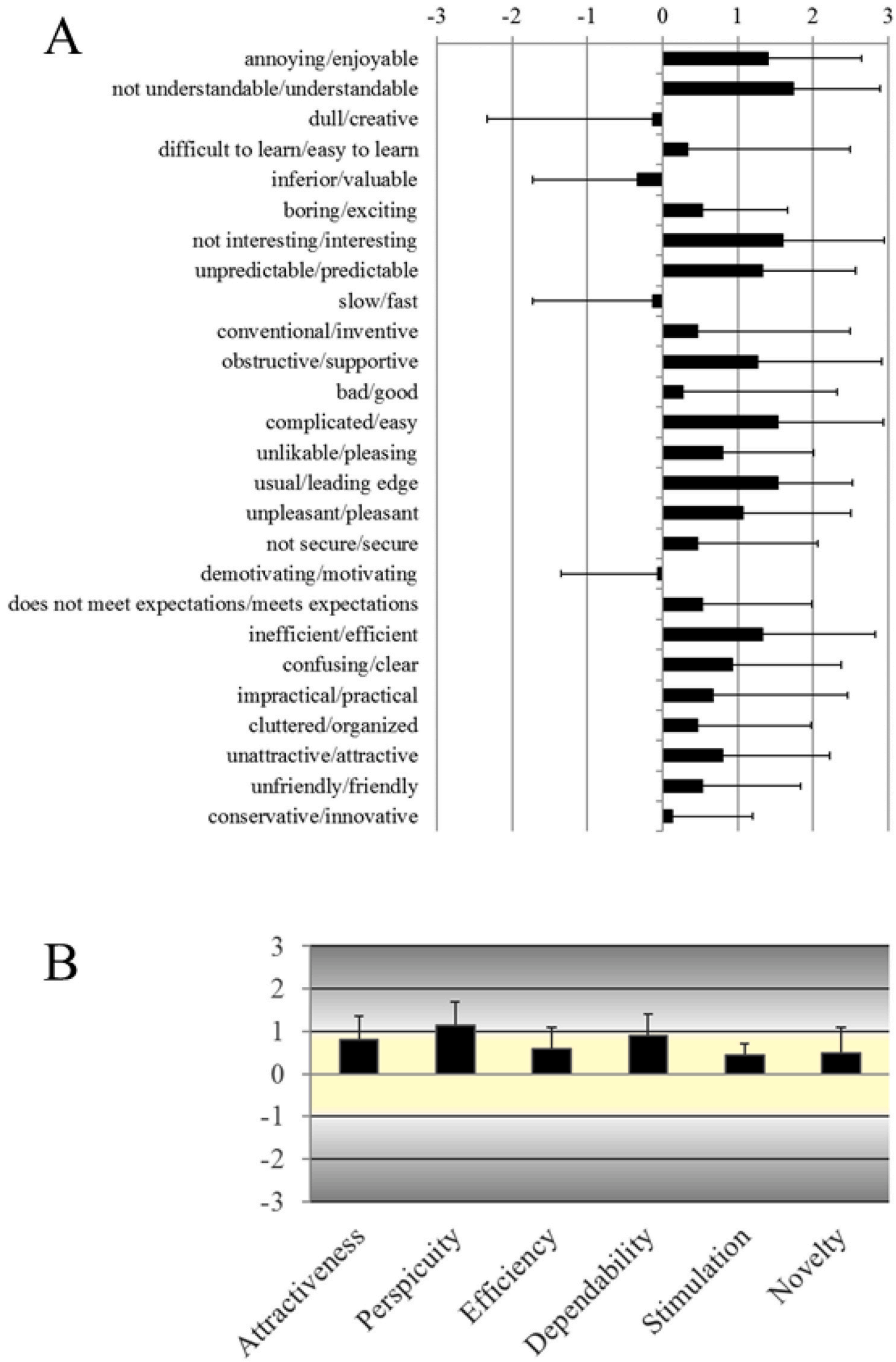

Fig. 4. Analysis of User Experience Questionnaire filled only after the use of Armrest® forearm support, per each item (A) and by grouped items (B). Note that negative values represent negative experiences while positive values represent positive experiences.

5. Conclusion

In conclusion, forearm, wrist, and finger postures are powerful predictors of carpal tunnel pressure, an important pathomechanical factors in the development of CTS (Viikari-Juntura and Silverstein, 1999). A moveable hand support (Armrest®), in contrast to no support, assured forearm elevation by means of a suspending pad resulting in lower average wrist extension and less time spent above wrist angle threshold levels. Furthermore, an almost frictionless moveable forearm support assured lower wrist manipulation that resulted in lower average ulnar-radial flexion and lower time spent above the threshold ulnar flexion levels. The respondents rated the moveable arm support as a tool that creates a feeling of clarity, reliability, efficiency, and attractiveness.

Author statement

Saša Jovanović: Conceptualization, Methodology, Investigation, Writing original draft; Boštjan Šimunič: Conceptualization, Methodology, Formal Analysis, Writing- Reviewing and Editing, Writing original draft, Writing – Reviewing & Editing, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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