Effects of Operation Type and Handle Shape of the Driver Controllers of High-Speed
Train on the Drivers' Comfort

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Abstract

The design of a high-speed train controller affects the driver's health, operating performance and even safety. Understanding the effects of the design factors on the physical ergonomics of a high-speed train driver controller is essential for optimizing performance and safety. This study experimentally investigated the role of the operation type and handle shape on the physical ergonomics of a driver controller for a high speed train. Two controllers and six handles with pyriform shape, T-shape, sphere shape, cylinder shape and conical frustum shape were used in the experiment. The results indicated that a controller of the sagittal rotation operation type could significantly reduce the workload of the upper limbs compared to a horizontal rotation operation type controller. The handle shape had significant effect on the wrist angles, hand pressures and subjective assessment scores of upper limb fatigue, wrist discomfort and palm discomfort. The handle shape influenced the wrist angles and hand pressures depending on how the participants held the handle. The results demonstrated that the preferred operation type was rotation in the

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parasagittal plane and that the handle shape should be convenient for operating with a downward-facing palm posture. Among the tested shapes, the pyriform shape and T-shape were considered to be preferable.

Relevance to industry

These findings can be used as a basis for the design of the driver controller for high-speed train and as a foundation for improving the operational performance of high-speed train driver in terms of safety.

Keywords: Driver controller, Physical ergonomics, Hand pressure

1. Introduction

Hand tools are ubiquitous and integral to technological progress. Working with a poorly designed hand tool for long periods can cause upper limb fatigue or discomfort, perhaps even resulting in musculoskeletal injury or carpal tunnel syndrome(Konz & Mital, 1990; Myers & Trent, 1988; Tung, Shorti, Downey, Bloswick, & Merryweather, 2014). A poorly designed hand tool can also reduce operation precision(Van Veelen, Meijer, Goossens, & Snijders, 2001), resulting in operation accidents. The driver controller is a hand tool used by a high speed train driver to set the traction or braking level of a high-speed train. The driver controller is the most frequently used tool on the driver's desk in a high-speed train. Furthermore, when driving the train, the high speed driver needs to hold the controller all time according to the high speed train operating rules. The design of the controller influences the driver's health and operation performance and, thus, indirectly influences the operational safety of the train.

Functionality, physical interaction and appearance, which are the factors that should be

1 considered in hand tool design, focus on the reliability, physical ergonomics and aesthetics of
2 hand tools, respectively(Kuijt-Evers, Groenesteijn, de Looze, & Vink, 2004). In the factors
3 identified above, physical interaction has many of its own metrics: posture and muscles, irritation
4 and pain of hand and fingers, irritation of hand surface, and handle characteristics(Kuijt-Evers et
5 al., 2004). The metrics correspond to the design factors of handle operation type, angle, size,
6 shape, and surface, among others (Michael Patkin, 2001).

7 Considerable research has been undertaken to analyze the effects of the above design
8 factors on the physical ergonomics of various hand tools, such as how the grip force(Lowndes,
9 Heald, & Hallbeck, 2015) is affected by the operation type; how wrist posture(Wang, Chung, &
10 Chen, 2000), wrist motion(Schoenmarklin & Marras, 1989a) and muscle fatigue(Schoenmarklin
11 & Marras, 1989b) are affected by the handle angle; how grip strength(Marcotte, Aldien, Boileau,
12 Rakheja, & Boutin, 2005; McDowell, Wimer, Welcome, Warren, & Dong, 2012), pinch grip
13 capacity(Ng & Saptari, 2014) and subjective comfort rating(Gonzalez, Salgado, & Moruno,
14 2015) are affected by the handle size; how the hand performance(Dianat, Nedaei, & Mostashar
15 Nezami, 2015), hand muscle load(Dong et al., 2007), wrist and finger muscles activation(Popp,
16 Lambercy, Müller, & Gassert, 2016), and grasping strategies(Seo & Armstrong, 2011) are
17 affected by the handle shape; and how musculoskeletal disorders(Singh & Khan, 2014) are
18 affected by the handle surface. Subjective methods such as questionnaires(Kuijt-Evers, Twisk,
19 Groenesteijn, Looze, & Vink, 2005), Borg RPE scales and Borg CR-10 scales(Eksioglu, 2006;
20 Li, Yu, & Zhang, 2013) and objective methods such as EMG(Agostinucci & McLinden, 2016;
21 Eksioglu, 2011; Hägg & Runeson, 2015), pressure mapping(Eksioglu & Kızılaslan, 2008; Kalra,
22 Rakheja, Marcotte, Dewangan, & Adewusi, 2015; Yun, Kotani, & Ellis, 1992) and grip

1 force(Eksioglu, 2004; Welcome, Rakheja, Dong, Wu, & Schopper, 2004) are common methods
2 used to determine the physical ergonomics of hand tools.

3 Most of the previous research has focused on the handles of various surgical instruments
4 or multipurpose instruments. Few studies have investigated the control handles of vehicles; those
5 that have done so include the investigation of repetitive strain injuries when using hydraulic-
6 actuation joystick controls in heavy vehicles(Murphy & Oliver, 2011; Oliver, Tingley, Rogers,
7 Rickards, & Biden, 2007), which indicate that the operator upper limb movement direction has
8 the most effect on upper limb angles and the dynamic armrest can significant decrease operator
9 shoulder muscle activation, studies on the effect of gender, speed and road condition on the grip
10 force of the steering-wheel in a full-size passenger car(Eksioglu & Kızılaslan, 2008), which
11 shows that the absolute force and net grip force values for male drivers are significantly higher
12 than those for female drivers while the vehicle speed and the road condition have no significant
13 effects on these response variables, and studies on the subjective comfort of driver controllers in
14 suburban electric trains(Stevenson, Coleman, Long, & Williamson, 2000), which show that the
15 position of the master controller and brake controller can significantly affect the satisfaction of
16 the driver.

17 The layout of the driver's desk, operation force, handle size, handle shape and operation
18 type are design factors that should be considered when designing a high-speed train driver
19 controller. There are a variety of standards and specifications associated with the design of high-
20 speed train driver controllers. UIC 651 specifies that driver controllers must be located in the
21 area of the optimal operational field for the driver(UIC 651, 2002). The operational forces of
22 driver controllers are defined in TB/T 1391-2007 (TB/T 1391, 2007). Moreover, the handle

diameter size of the driver controller is specified in GB/T 14775-1993 to be in the range of 35 to 50mm with a recommendation size of 40mm. The operation type of the driver controller is not subjected to compulsory requirements, although the operation type must have one of only two forms: rotation movement in the horizontal plane and rotation movement in the parasagittal plane, according to ISO9355-3(ISO 9355-3, 2006; Dongbo Li, Beiyuan Guo, Xiuquan He, Yongting Liang, & Liming Li, 2013). The handle shape is also not subjected to compulsory requirements, although there are some recommended handle shapes provided by the UIC standard(UIC 612, 2009). In China, high speed train drivers have also reported discomfort in the arms and hands and have complained about the unreasonable design of the handle shape and operation type. Hence, in the present study, two repeated-measurement experiments were conducted to investigate the effects of controller operation type and controller handle shape on the comfortable use of the driver controller in a high-speed train. In the experiments, the wrist angle, grip pressure and subjective assessment scores of upper limb fatigue, wrist discomfort and palm discomfort were used as criteria to determine the suitable operation type and handle shape for the driver controller in a high-speed train. These results can be used as a basis for the design of driver controllers.

2. Method

2.1. Participants

In total, fifteen male participants were recruited from the student body at Beijing Jiaotong University. The participants were all right-handed. Table 1 shows the demographics of the participants. The participants were not high-speed train drivers but were trained to be familiar with the methods for operating driver controllers on the driver's desk. Participants with previous

hand and upper extremity injuries, musculoskeletal disorders and surgeries were excluded from the study. Participants were asked to avoid strenuous exercise and physical activity for twenty-four hours before the experiment to preclude possible variations in fatigue sensation. The participants were able to understand the test procedures.

Table 1. Demographics of the participants.

	<i>Range</i>	<i>Mean</i>	<i>SD</i>
Age (years)	21-29	23.27	2.43
Weight (kg)	60-79	70.87	6.10
Stature (cm)	170-179	174.20	2.91
Hand length (mm)	173-194	187.13	6.96
Hand breadth^a (mm)	78-94	87.47	4.96
Hand thickness (mm)	25-40	31.47	4.55
Grip diameter^b (mm)	43-48	45.37	1.48

^a Hand breadth across finger knuckles.

^b Thumb-middle finger grip diameter.

2.2. Experiment setup

A real CRH380A traction controller (see Figure 1(a)) and a real CRH380A braking controller (see Figure 1(b)) were used in the study. The traction controller is a hand tool used to increase or decrease power, and the braking controller is a hand tool used to apply the brakes. There were two handles on the traction controller. As shown in Figure 1(a), to the left of the two handles is the traction level set handle and to the right is the direction set handle. Only the traction level set handle was used in the study. The handles of the two controllers featured a quick release structure and could be changed easily. The operation types of the traction controller and the braking controller were the parasagittal plane rotation type and the horizontal plane rotation type, respectively. The operation type of the braking controller could be changed to the

parasagittal plane rotation type by rotating the controller 90° to the left, as shown in Figure 1(c). The traction controller has a total of eleven traction level positions. The operation force of each traction level is 3.0 ± 0.5 kgf. The braking controller had a total of eight braking level positions. The operation force of each braking level is 1.3 ± 0.6 kgf.

Figure 1. The controllers used in the study. (a) CRH380A driver's traction controller. (b) CRH380A driver's braking controller. (c) CRH380A driver's braking controller with the controller rotated 90° to the left.

Two simulated driver desks (desk I and desk II) were designed to provide participants with operation interfaces to use the controllers (see Figure 2). The length, width and height of the desks were 1200mm, 350mm and 900mm, respectively. A manual adjusted footrest whose angle range could be adjusted from 15° to 25° was placed under the desk. The space for knees, which is the space between the topside of the footrest and the underside of the desk, was 667mm. All dimensions conformed to the requirements of UIC 651(UIC 651, 2002). The traction controller and the braking controller were assembled on desk I with normal installation mode and installation mode of rotating the controller 90° to the left, respectively. The normal installation mode represents the way the controller is installed on a real driver desk of CRH380A. The

braking controller was assembled in desk II with the normal installation mode. Participants could operate the controller from both sides of the desk to ensure that they used their right hands. The desks came with a driver seat that was adjustable to ensure that the participants could obtain the most comfortable sitting position.

Figure 2. Simulated desks used in the study. (a) Simulated desk I: two controllers on the desk; the right controller is the traction controller, and the left one is the braking controller assembled with the installation mode of rotating the controller 90° to the left. (b) Simulated desk II: a braking controller assembled on the desk.

From a survey of fifty-two high speed trains and electric multiple unit trains around the world, six handles, representing the typical shapes of high-speed train driver controllers, were prepared. As shown in Table 2, the abbreviated name of the cylinder shape handle for the braking controller is RH, and the abbreviated names of the pyriform shape, T-shape, sphere shape, cylinder shape and conical frustum shape handles for the traction controller are P, T, S C and F, respectively. The dimensions of the handles were designed based on the UIC standard(UIC 612, 2009). The handles were made of acrylonitrile butadiene styrene (ABS), and their surfaces were

1 all polished.

Table 2. Detailed information of the six handles

Abbreviate Name	RH	P	T	S	C	F
Shape	Cylinder	Pyriform	T-shape	Sphere	Cylinder	Conical Frustum
Image
Dimension	Ø40mm	Length:76mm Width:100mm Height:72mm	Length:127mm Width:40mm Height:72mm	SØ48mm	Ø40mm	Height:42mm Large end:Ø40mm Small end:Ø27mm

2.3. Apparatus

A Canon EOS1000D camera was used to record the wrist radial-ulnar deviation and flexion-extension from the top view and right side view, respectively.

A Tekscan grip pressure mapping system (see Figure 3(a)) was used to gather the hand pressure of the participants. The system had a VersaTek cuff to gather, process and send data from a Tekscan pressure mapping sensor (#4256E, pressure sensitive range of 0 - 345 kPa) to a computer. The scan rates of the system were up to 750Hz. Two sensor equipped right hand gloves (glove I and glove II) were prepared (see Figure 3(b) and (c)) to ensure that the grip pressure of the entire palm could be measured. Before the experiment, the Tekscan grip pressure mapping system was calibrated using the Tekscan recommended method(Tekscan Inc., 2011).

Figure 3. Grip pressure mapping system. (a) Tekscan grip pressure mapping system. (b) Sensor equipped glove I. (c) Sensor equipped glove II.

2.4. Experimental design

Two experiments, experiment A and B, were designed to investigate the effects of the operation type and handle shape, respectively, on the physical ergonomics of the driver controller. The experimental scenarios and usages of the desks, controllers and handles are shown in Table 3. As previously mentioned, the traction controller has a total of 11 traction level positions. The operation force of each traction level is $3.0 \pm 0.5 \text{ kgf}$. The braking controller had a total of eight braking level positions. The operation force of each braking level is $1.3 \pm 0.6 \text{ kgf}$. We can find that the operation force is different between the two controllers. So in experiment A, we used only the braking controller, and experiment B, we used only the traction controller to exclude the influence of operation force. In experiment A, the independent variable was the operation type and the response variables were the wrist angle and subjective scores of upper limb fatigue and wrist discomfort. In experiment B, the independent variable was the handle shape and the response variables were wrist angle, hand grip pressure, and subjective scores of upper limb fatigue, wrist discomfort and palm discomfort.

Table 3. Experimental scenarios and usages of the desks, controllers and handles.

	Experiment A		Experiment B
Controller	Braking controller		Traction controller
Desk	Desk II	Desk I	Desk I
Installation mode of controller	Controller's normal installation mode (see Figure 1(b))	Rotating the controller 90° to the left (see Figure 1(c))	Controller's normal installation model (see Figure 1(a))
Handle shape	RH	RH	P, T, S, C, F
Operation type	Horizontal plane rotation	Parasagittal plane rotation	Parasagittal plane rotation

Before the experiment was started, a signed informed consent document was obtained from the participants. Subsequently, information on the participant age and weight was gathered. The participants' stature and hand sizes were also measured. The experimental setup was described to all participants.

After adjusting the footrest and the driver's seat to the most comfortable position, each participant sat straight in the driver's seat in front of the desk. During the experiment, the participants operated the controller with their right hand following the instructions of the experimenter.

Experiment A was conducted in two steps:

(1) The participants operated the braking controller with handle RH for each of the two operation types. The experimenter used the camera to capture images at each of the eight positions of the braking controller.

(2) After continuously operating the braking controller in each of the two operation planes for thirty min, each participant filled out two visual analog scale questionnaires to report their sensations of upper limb fatigue and wrist discomfort. The upper limb fatigue scale and

wrist discomfort scale ranged from no exertion at all (score 0) to maximal exertion (score 10).

Experiment B was conducted in four steps:

(1) The participants operated the traction controller with handles P, T, S, C and F. The experimenter used the camera to capture images at each of the 11 positions of the traction controller.

(2) The participants donned glove I and moved the handle of the traction controller back and forth to complete a round trip operation. Meanwhile, the grip pressure mapping system continuously recorded the grip pressure of the participants. The grip pressure mapping frame was recorded at a sampling rate of 5Hz.

(3) The participants donned glove II and repeated the same operation as step (2).

(4) The participants took off the glove and continuously operated the traction controller with each of the five handles for thirty min. Subsequently, the participants filled out three visual analog scale questionnaires to report their sensations of upper limb fatigue, wrist discomfort and palm discomfort. The upper limb fatigue scale, wrist discomfort scale and palm discomfort scale ranged from no exertion at all (score 0) to maximal exertion (score 10).

A cruise control system is one of the standard configurations in the current high speed train. Hence, the high speed train driver does not need to operate the driver controllers to set the speed when the train is in the cruise phase. However, when the driver tries to stop the train, or when the cruise control system is out of service, the driver needs to use the controllers continuously to set the train to run at a planned speed. Thus, the scenario of continuous operation was realistic and it is the practice in real life. Because the purposes of these two steps (step 2 in experiment A and step 4 in experiment B) were to test the fatigue degree of the upper limb, the

1 participants were required to operate the controller for a sufficiently long time in order to feel
2 fatigue. Thus, the participants were asked to continuously operate the controller for thirty min in
3 the experiments.

4 Each participant attended only one trial with one handle per day to exclude the influence
5 of fatigue. Seven days were required for each participant to finish all the experiments. The
6 participants took part in the experiments in a random order. The study protocol was approved by
7 the State Key Laboratory of Rail Traffic Control and Safety Institutional Review Board.

8 2.5. Data analysis

9 2.5.1. Wrist angles

10 Because radial deviation, ulnar deviation, flexion and extension all have a significant
11 influence on wrist discomfort(Carey & Gallwey, 2000), the radial and ulnar deviation, as well as
12 flexion and the extension, were recorded as the radial-ulnar deviation angles and flexion-
13 extension angles, respectively. As illustrated in Figure 4, the radial-ulnar deviation angles and
14 flexion-extension angles relative to the forearm were measured by a photographic measurement
15 method.

Figure 4. Measurement of wrist angles. (a) Measurement of radial-ulnar wrist angle. (b)

Measurement of flexion-extension wrist angles.

For each position i of the controllers, we measured the radial-ulnar deviation angle α_i and flexion-extension angle β_i . The maximum radial-ulnar deviation angle $\alpha_{\max}$, the maximum flexion-extension angle $\beta_{\max}$, the mean radial-ulnar deviation angle α_m and the mean flexion-extension angle β_m were calculated as follows:

$$\alpha_{\max} = \max_{i \in N} \alpha_i \quad (1)$$

$$\beta_{\max} = \max_{i \in N} \beta_i \quad (2)$$

$$\alpha_m = \frac{1}{N} \sum_{i=1}^N \alpha_i \quad (3)$$

$$\beta_m = \frac{1}{N} \sum_{i=1}^N \beta_i \quad (4)$$

where N are the position numbers of the controllers.

2.5.2. Grip pressure

There were nineteen measurement areas on the right hand in experiment B, as shown in Figure 5. Regions 16, 17 and 19 were the most sensitive regions of the hand to surface pressure (Fransson-Hall & Kilbom, 1993). Hence, the pressure data of regions 16, 17 and 19 were used in the further analysis. The pressure data were processed using Grip Research version 6.51 (shipped with the Tekscan grip pressure mapping system). The maximum pressure force and mean pressure force of the regions were calculated. Taking region 19 as an example, let P_{nij} be the pressure force of the sensor cell at data frame n , row i and column j of the region; the maximum pressure force is $P_{\max} = \frac{1}{N} \sum_{n=1}^N \max_{ij} P_{nij}$, where N is the total frame number; the mean pressure force is $P_m = \frac{1}{N} \sum_{n=1}^N (\frac{1}{M} \sum_{i=1}^I \sum_{j=1}^J P_{nij})$, where M is the number of cells in which $P_{nij} > 0$ and I and J represent the row number and column number, respectively, of region 19.

Figure 5. The most sensitive regions of the hand to surface pressure

2.5.3. Statistical methods

Means and standard deviations for each wrist angle, hand pressure and sensation score were calculated. One-way ANOVA with Tukey multiple comparison post hoc test was used to compare the data within the group; $p < 0.05$ was considered significant.

3. Results

3.1. Operation type

3.1.1. Effect on wrist angle

Table 4 shows the wrist angles for different operation types. The operation type had no significant effect on the maximum radial-ulnar deviation angle ($F(1, 28) = 1.173, p = .288, \eta^2 = .040$), mean radial-ulnar deviation angle ($F(1, 28) = .274, p = .605, \eta^2 = .010$), maximum flexion-extension angle ($F(1, 28) = .742, p = .396, \eta^2 = .026$) or mean flexion-extension angle ($F(1, 28) = .294, p = .592, \eta^2 = .010$).

Table 4. Wrist angles for different operation types.

Wrist angle	Operation type	$M(^{\circ})$	$SD(^{\circ})$
Maximum radial-ulnar deviation angle	Horizontal plane rotation	31.82	3.24
	Parasagittal plane rotation	30.51	3.37
Mean radial-ulnar deviation angle	Horizontal plane rotation	16.55	2.74
	Parasagittal plane rotation	16.00	2.95
Maximum flexion-extension angle	Horizontal plane rotation	25.90	3.77
	Parasagittal plane rotation	24.70	3.85
Mean flexion-extension angle	Horizontal plane rotation	20.00	3.20
	Parasagittal plane rotation	19.32	3.68

In experiment A, the participants held the handle with the right hand. Because the handle had a cylindrical shape, the participants wrapped their thumb and fingers around the handle to hold it. Different operation types led to different palm orientations. When rotating the handle in the horizontal plane, the participants held the handle with the palm facing downward; when rotating in the parasagittal plane, the palm faced inward. In experiment A, only the braking controller was used; the parameters that could influence the wrist angle, such as handle shape and operation stroke length, were the same in the experiment. Hence, the effect of the operation type on the radial-ulnar deviation angle and flexion-extension angle was not significant.

3.1.2. Effect on subjective score

The operation type had no significant effect on the wrist discomfort score ($F(1, 28) = .189, p = .667, \eta^2 = .007$). The participants did not differ on the reported wrist discomfort score for the horizontal plane rotation operation ($M = 4.8667, SD = .8338$) or for the parasagittal plane rotation operation ($M = 5.0000, SD = .8452$). The result that no difference was found in the wrist discomfort score between the two operation types also supported the above finding.

The operation type had a significant effect on the upper limb fatigue score ($F(1, 28) = 37.030, p < .0001, \eta^2 = .569$). The reported upper limb fatigue score for the horizontal plane rotation operation ($M = 5.8000, SD = .7746$) was significantly greater than that of the parasagittal plane rotation operation ($M = 4.2667, SD = .5936$).

3.2. Handle shape

3.2.1. Effect on wrist angle

Figure 6 shows the wrist angles for different handle shapes. Handle shapes had a significant effect on the maximum radial-ulnar deviation angle ($F(4, 70) = 48.801, p < .0001, \eta^2 = .736$), mean radial-ulnar deviation angle ($F(4, 70) = 14.903, p < .0001, \eta^2 = .460$), maximum flexion-extension angle ($F(4, 70) = 59.248, p < .0001, \eta^2 = .772$) and mean flexion-extension angle ($F(4, 70) = 43.732, p < .0001, \eta^2 = .714$).

Figure 6. Wrist angles for different handle shapes. The values in the bar graph are represented as means $\pm$ SE.

*** $p \leq 0.001$; ** $p \leq 0.01$

3.2.2. Effect on grip pressure

Figure 7 shows the hand pressure for different handle shapes. Handle shapes had a significant effect on the maximum pressure ($F(4, 70) = 280.816, p < .0001, \eta^2 = .941$) and mean pressure ($F(4, 70) = 87.873, p < .0001, \eta^2 = .834$) of hand region 16, maximum pressure ($F(4, 70)$

1 = 367.783, $p < .0001$, $\eta^2 = .955$) and mean pressure ($F(4, 70) = 231.469$, $p < .0001$, $\eta^2 = .930$) of
2 hand region 17, and maximum pressure ($F(4, 70) = 50.040$, $p < .0001$, $\eta^2 = .741$) and mean
3 pressure ($F(4, 70) = 181.592$, $p < .0001$, $\eta^2 = .912$) of hand region 19.

Figure 7. Hand pressure for different handle shapes. The values in the bar graph are represented as means $\pm$ SE.

*** $p \leq 0.001$; ** $p \leq 0.01$

3.2.3. Effect on subjective score

Table 5 and Figure 8 show the sensation score of upper limb fatigue, wrist discomfort and

1 palm discomfort for different handle shapes. The handle shapes had a significant effect on the
2 sensation of upper limb fatigue ($F(4, 70) = 54.754, p < .0001, \eta^2 = .758$), sensation of wrist
3 discomfort ($F(4, 70) = 52.464, p < .0001, \eta^2 = .750$) and discomfort sensation of palm regions 16
4 ($F(4, 70) = 224.837, p < .0001, \eta^2 = .928$), 17 ($F(4, 70) = 224.635, p < .0001, \eta^2 = .928$) and 19
5 ($F(4, 70) = 45.423, p < .0001, \eta^2 = .722$).

Table 5. Average sensation score of upper limb fatigue, wrist discomfort and palm discomfort for different handle shapes.

Shape	Upper Limb	Wrist	Palm Region 16	Palm Region 17	Palm Region 19
P	3.87	2.8	1.47	0.8	2.53
T	4.07	2.93	4.27	4.8	3.87
S	5.47	4.6	5.53	4.87	3.93
C	6.67	6.13	0.73	1.73	1.33
F	5.47	4.8	6.67	7.4	3.8

6

Figure 8. Sensation of upper limb fatigue, wrist discomfort and palm discomfort for different handle shapes. The values in the bar graph are represented as means $\pm$ SE.

*** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$

3.2.4. Correlation between grip pressure and subjective score

There was a statistically significant positive correlation between the maximum pressure and discomfort sensation of palm regions 16, 17, and 19, $r(15) = 0.771$, $p = 0.001$. The positive correlation meant that, in general, participants who received more maximum pressure tended to

rate higher on the palm discomfort sensation score. The effect size of $r=.771$ was considered very large for this area of research.

3.3. *Influence of the controllers*

Although experiment A and experiment B were two independent experiments, and two controllers with different operation forces were used in the experiments. Two cylindrical handles of same diameter were used in both experiments with same parasagittal plane rotation operation type. Experiment data shows that operation force had a significant effect on the sensation of upper limb fatigue ($F(1,28) = 117.818, p < .0001, \eta^2 = .808$) and sensation of wrist discomfort ($F(1,28) = 13.669, p = .001, \eta^2 = .328$). Experiment data also shows when the operation force increased, the sensation score of upper limb fatigue and wrist discomfort increased.

4. Discussion

As described in section 3.3, the operation force of controller did have an effect on the sensation score of upper limb fatigue and wrist discomfort. To exclude the influence of the different operation force of the different controller, experiment A and experiment B were designed to explore the influence of operation type and handle shape respectively. In Experiment A, we used only the braking controller, and in experiment B, we used only the traction controller.

In experiment A, when rotating the handle in the parasagittal plane, the upper arm abduction angles were close to zero. The wrist angle, elbow flexion-extension angle and shoulder flexion-extension angle changed with the change in the braking position of the controller. Because the upper arm abduction angles were kept mostly stable, the upper arm, forearm and hand roughly moved in a 2D plane. When rotating the handle in a horizontal plane, the upper arm

1 abduction angle changed with the change in the braking position. In the experiment, the upper
2 arm abduction angle could be up to 30° , which was out of the comfortable abduction angle
3 range(0° to 10°) for the upper arm in the shoulder joint(A. Aarås, Westgaard, & Strandén, 1988).
4 Because of the change in the upper arm abduction angle, the upper arm, forearm and hand moved
5 in a 3D space. The upper limb needed to exert more muscular strength in the 3D space than in
6 the 2D plane to overcome the resistance operation force of the braking controller. Hence, the
7 parasagittal plane rotation type can significantly reduce the workload of the upper limbs. When
8 designing a driver controller, the parasagittal plane rotation type should be given precedence
9 over the horizontal plane rotation type.

10 As shown in Figure 6, the wrist angles of handle C (cylinder shape) were much different
11 than that of the other four handles in experiment B. The controller in experiment B was of the
12 parasagittal plane rotation type. In the experiment, each participant held the cylinder handle
13 between the thumb and all four fingers at 90° to the hand margins, with the palm facing inward
14 (see Figure 9(e)). When rotating the handle in the parasagittal plane, the participants bent their
15 wrists to the little finger side or the thumb side to maintain their transverse grip posture while
16 keeping their wrist from bending left to right. Hence, handle C featured the largest radial-ulnar
17 deviation angles and the smallest flexion-extension angles. Wrist radial-ulnar movement was
18 more uncomfortable than wrist flexion-extension movement (Rempel, Keir, & Bach, 2008).
19 Hence, as shown in Figure 8(a) and (b), handle C received the highest score for the sensation of
20 upper limb fatigue and wrist discomfort.

21 Handles P, T, S and F were held with the thumb and fingers placed radially around the
22 handle while the palm faced downward. When moving the handles, the participants tended to

1 keep their wrists from bending left to right, which was the radial side and the ulnar side,
2 respectively. Hence, handle shapes P, T, S and F had no significant effect on the radial-ulnar
3 deviation angles (see Figure 6(a) and (b)).

4 The participants used the thenar eminence, hypothenar eminence and distal portion of all
5 fingers to grip handle P (see Figure 9(a)). Because these contact areas were scattered throughout
6 the hand, it was easy for the participants to adjust their hand postures to reduce the flexion-
7 extension angle. For example, when pushing the handle, the participants could reduce the
8 extension angle using the hand areas of the thenar eminence and hypothenar eminence (see
9 Figure 9(a)). When holding handle T, the contact areas were the part between the thumb and the
10 index finger, the center part of the palm and the intermediate portion of the fingers (see Figure
11 9(b)). The method of holding handle T also provided the participants with a high level of hand
12 posture adjustment. The participants held handles S and F with the center of the palm (see Figure
13 9(c) and (d)) because of the small size of the two handles. It was difficult for the participants to
14 adjust their holding posture owing to the small contact area with the hand. Hence, handles P and
15 T resulted in smaller flexion-extension angles than handles S and F (see Figure 6(c) and (d)).
16 Relatively, as shown in Figure 8(a) and (b), the sensation scores of upper limb fatigue and wrist
17 discomfort for handles P and T were smaller than those for handles S and F.

Figure 9. Methods for holding the handles. (a) The method for holding handle P. (b) The method for holding handle T. (c) The method for holding handle S. (d) The method for holding handle F. (e) The method for holding handle C.

The handle shapes, as well as the method by which the participants held the handles, also affected the maximum pressure and mean pressure of each contact region (see Figure 7). Relative to the mean pressure, the results of the subjective palm discomfort sensations agreed with the results of the maximum pressure for each region (see Figure 8(c-e)). This finding was rational because the higher the pressure, the higher the stress on the palm. In this study, we used the maximum pressure to perform further analysis. When holding handle F in the palm, the sharp edge of the conical frustum concentrated the contact pressure between the hand and the handle. Hence, the conical frustum handle F had the largest maximum pressure for regions 16 and 17. The participants also held spherical handle S with the center of the palm; although the spherical

1 handle had a smooth surface, because of its small volume, the pressure was also relatively
2 concentrated on the center of the palm. Hence, it had the second-highest maximum pressure for
3 regions 16 and 17. The part of the hand between the thumb and the index finger is included in
4 region 17. Hence, the maximum pressure of operation for handle T was not significantly different
5 from the pressure of using handle S for region 17. However, the maximum pressure of handle T
6 for region 16 was significantly lower than that of handle S. Handle P had the lowest maximum
7 pressure for regions 16 and 17 because the contact areas were scattered throughout the hand
8 when holding it. The participants held handle C with the palm facing inward. The posture was a
9 bit more particular. However, handle C was the longest handle and had a large contact area, so it
10 had a high maximum pressure for region 17; however, the value was less than those of handles T
11 and S. Particularly, the pressure for region 19 was zero, meaning that there was no contact
12 between handle C and the hand.

13 **5. Conclusions**

14 The current study examined the effects of operation type and handle shape on the
15 physical ergonomics of driver controllers for high-speed trains. The results indicated that there
16 was no significant difference in the wrist angles between the two operation types and that sagittal
17 rotation operation could significantly reduce the workload of upper limbs compared to the
18 horizontal rotation operation. The results of the experiments showed that the handle shape had a
19 significant effect on the wrist angles, the pressure and subjective assessment scores of upper limb
20 fatigue, wrist discomfort and palm discomfort. The handle shape influenced the wrist angles and
21 subjective assessment scores of the participants through the method by which the participants
22 held the handle. The cylindrical handle had the worst subjective assessment results because the

participants held it with the palm facing inward and bent their wrists to the little finger side or the thumb side to maintain their transverse grip posture. The pyriform handle and T-shaped handle received good subjective assessment in terms of arm fatigue and wrist discomfort because the participants could freely adjust the hand posture when operating them. Hand pressure was also influenced by the holding method. Handle P received the lowest comprehensive pressure comfort score because the contact areas were scattered throughout the hand when holding it. When designing a driver controller for high-speed trains, the parasagittal plane rotation type should be given precedence over the horizontal plane rotation type, and the handle shape should be convenient for operation with the posture of the palm facing downward. The pyriform shape and T-shape could be considered as preferable.

The present research discussed the effect of operation type and handle shape on the physical ergonomics of driver controller under static conditions. High speed train vibrations may have an effect on the results. Future research should explore the influence of high speed train vibrations on the effects of operation type and handle shape on the physical ergonomics of driver controller under dynamic conditions.

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