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ORIGINAL ARTICLE

Passive haptics: greater impact presented by pulsive damping brake of DC motor and physical indices for perceived impact

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Abstract
This study investigated the perceptual characteristics of pulsive brakes presented by passive haptic interfaces. A passive-type haptic interface based on the damping brake of a DC motor was used to generate impact; this has merits of inherent safety and energy efficiency. This haptic interface expresses impacts by resisting the operator's hand via the resistive force generated by a damping brake. In terms of impulse or momentum, maximum impact was achieved by continuously operating the damping brake after colliding with a virtual object. We found that instantaneous release of the brake immediately after collision increases the perceived impact. We computed several physical indices associated with the force against the hand as well as the hand velocity and investigated their relationships with the perceived magnitudes of the impacts. A high correlation was found between the absolute change ratio of the hand velocity and the perceived impact, which suggests that instantaneously releasing the brake is effective in terms of impact perception. Our findings indicate that the performance of passive haptic interfaces can extend physical limits, and the range of applications can be expanded by incorporating human perceptual characteristics.

Keywords Passive haptic interface · Impact perception · Damping brake

1 Introduction

Haptic interfaces, in which the system is passively controlled in accordance to an external force, have been investigated by many researchers with a focus on high inherent safety and energy efficiency (Goswami et al. 1990; Davis and Book 1997; Scilingo et al. 2003). As most objects surrounding us are static, haptic interactions with them can be achieved by using reactive resistances. For instance, surface texture can be expressed using a passive haptic interface that features resistive force (Minsky et al. 1990; Okada et al. 2017, 2018). Passive force interfaces are promoted as safe and stable force-feedback devices for wearable robots or applications developed for untrained users (Hirata et al. 2007; Koyama et al. 2002; Winter and Bouzit 2007; Kikuchi et al. 2009; Asbeck et al. 2015; Ohashi et al. 2017). In the present manuscript, haptic systems that reduce the kinetic energy of the user are termed as passive haptic systems, regardless of the type of mechanical elements or actuators used to produce forces.

However, because passive haptic interfaces do not generate any energy in order to apply it against the operator, it is difficult to model impact-based feedback, which requires a large output force. This may become problematic when passive haptic interfaces are used to generate feedback forces for teleoperation robotics or virtual reality systems, in which dealing with information about contacts or collisions with an object (Lim et al. 2007; Seth et al. 2011; Hachisu and Kajimoto 2017; Wu et al. 2017; Culbertson and Kuchenbecker 2017) is important. Using active haptic interfaces is effective to express impact, provide a large impulsive force to an operator (Vander Poorten and Yokokohji 2007; Constantinescu et al. 2005), or rapidly increase the reactive force (Lawrence et al. 2000; Han and Choi 2010; Ikeda and Hasegawa 2009). It is believed that the physically maximum impact in passive haptic interfaces can be achieved by initiating the maximum brake or resistive force at the moment of collision. However, this method is not necessarily the best for presenting a perceptually maximum impact.

In a previous study, we devised a passive haptic interface based on the damping brake of a DC motor (Okada et al.

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2016a, b). For this haptic interface, physically maximum impact is achieved by the continuous function of the damping brake following collision with a virtual object. We previously empirically demonstrated that a brake with preceding pulsive brakes increases the operator's perception of impact (Okada et al. 2016a, b). However, only two types of pulsive brakes were tested therein, and the mechanism of the perception was not discussed. In this study, to determine the kind of pulsive-brake operation that can evoke enhanced perceived impact, we compared the physically maximum brake and seven types of pulsive brakes using a passive haptic interface based on a DC motor. Furthermore, to investigate the link between physical stimuli and impact perception, we calculated some physical quantities from contact force and hand velocity at the moment of collision and analyzed the correlation between the physical quantities and the perceived impact.

Pulsive brakes generate high-frequency components in presenting the impact. Such high-frequency force or vibrotactile feedback superimposed upon quasi-static reactive forces, following Hooke's law, delivers more accurate information regarding the colliding virtual objects in terms of the type of material and stiffness (Wellman and Howe 1995; Okamura et al. 2001; Hwang et al. 2004; Kuchenbecker et al. 2006). For instance, Hwang et al. (2004) demonstrated that transient reactive forces that nullified the momentum of a contactor as quickly as possible increased physical and perceived stiffness compared with a wall, simply represented by Hooke's law. Vibrotactile actuators that produce high-frequency components more easily than force displays are also effective for the same purpose (Wellman and Howe 1995; McMahan and Kuchenbecker 2009). The present study realizes similar principles by using a passive method, whereas the earlier studies used active force or vibrotactile displays.

A promising application of the present study is, for example, a user interface for assistive robots such as a walker, i.e., a hand-guided four-wheeled cart for those with locomotive disabilities. Some of the pre-existing robots (e.g., RT. Works, https://www.rtworks.co.jp/, 1, Dec., 2019) are equipped with electromagnetic motors to not only counteract the self-weight of a walker robot, but also prevent abrupt acceleration, among other purposes. In addition to these functions, passive haptic forces can be utilized to guide and navigate the walker's user via a combination of impact and other stimuli, including virtual bumps or friction on the road. Another application of such systems is in gaming and entertainment systems, for which the inherent safety shall be realized.

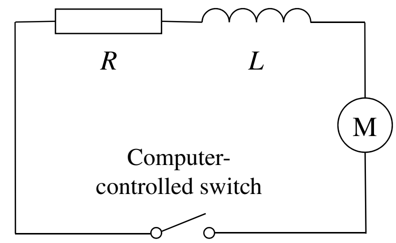


Fig. 1 Computer-controlled short circuit of the DC motor. Adapted from Okada et al. (2016a, b)

2 Apparatus: passive haptic interface based on damping brake of a DC motor

2.1 Principle: damping brake of a DC motor

We utilized the damping brake of a DC motor as the passive element of the haptic interface (Okada et al. 2016a, b). The damping brake's function is activated in a DC motor when its terminals are shorted. Figure 1 shows a shorted circuit of a DC motor with a computer-controlled switch. R and L are the resistance and inductance of the circuit, respectively. When the circuit is shorted by the switch, while the motor is rotating, a brake torque is generated by the back electromotive force of the motor. The relationship between the brake torque $\tau(t)$ and the rotation speed of the motor $\omega(t)$ is based on Kirchhoff's law and is given as follows:

$$\frac{L}{R}\frac{\mathrm{d}\tau(t)}{\mathrm{d}t} + \tau(t) = -\frac{K^2}{R}\omega(t), \tag{1}$$

where K is the torque constant of the motor. Provided that the inductance L is negligible, the brake torque $\tau(t)$ is proportional to the rotation speed $\omega(t)$, in other words, the damping brake of the DC motor functions as a viscous resistance. This effect can be used, for example, to improve the system passivity to avoid undesired oscillation (Mehling et al. 2005).

2.2 Passive haptic interface

Figure 2 shows the passive haptic interface that uses the damping brake of a DC motor. The DC motor (RE-40, Maxon motor, Switzerland, reduction ratio: 12, inductance: 0.025 mH, resistance: 0.115 Ω, torque constant: 16.4 mNm/A) was vertically fixed on the frame, and its output shaft was connected to a crank with a handle. Short circuiting of the motor was controlled by a mechanical relay (G6L, Omron, Japan, resistance: less than 0.1 Ω). The rotation angle of the motor was measured using a 1024-pulse optical encoder. The electrical time constant of the motor

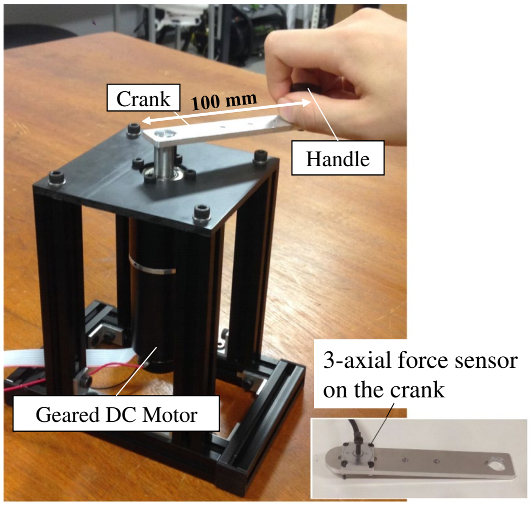


Fig. 2 Passive haptic interface based on the damping brake of a DC motor. Adapted from Okada et al. (2016a, b)

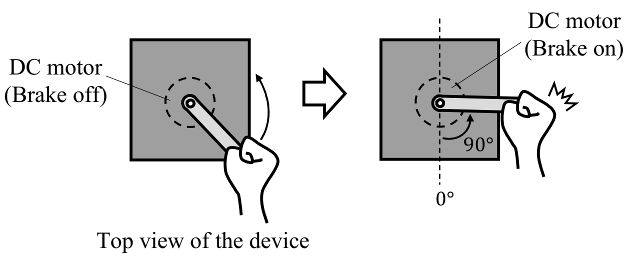


Fig. 3 Presentation of impact using the damping brake of a DC motor. Adapted from Okada et al. (2016a, b)

was 0.21 ms, and the responsivity of the relay was 1.1 ms. The total time of these is the delay from the initiation of stimuli to the abrupt changes in force and velocity. We did not perceive any effects from contact chattering. An operator rotating the crank from front-to-back experiences an impact at an angle of 90 deg, as shown in Fig. 3. At that point, the circuit is shorted, and the motor applies a brake abruptly.

The force applied against the hand of the operator was measured using a force sensor (USL06-H5, Tec Gihan, Japan) between the handle and crank. We used the force component along the direction of hand motion for the analysis. The linear drift of the sensor outputs was removed by using the sensor values immediately before and after each trial.

2.3 Physically maximum impact

When presenting impacts by using passive haptic interfaces, resistive force is generated against the movement of the operator (see Fig. 4a). Therefore, a physically maximum impact is achieved by continuously resisting the movement of the operator; more specifically, by increasing the impulse and thus decreasing the momentum of the operator's hand as much as possible. Thus, for presenting impacts based on the damping brake of the DC motor, we used a stepwise brake that continuously activates at the moment of collision, which is the best method to present physically maximum impact, as shown in Fig. 4b. Owing to this brake, the force applied on the operator and the hand velocity continue to increase and decrease after the collision (see Fig. 4c), resulting in maximization of the impulse or derived change of momentum.

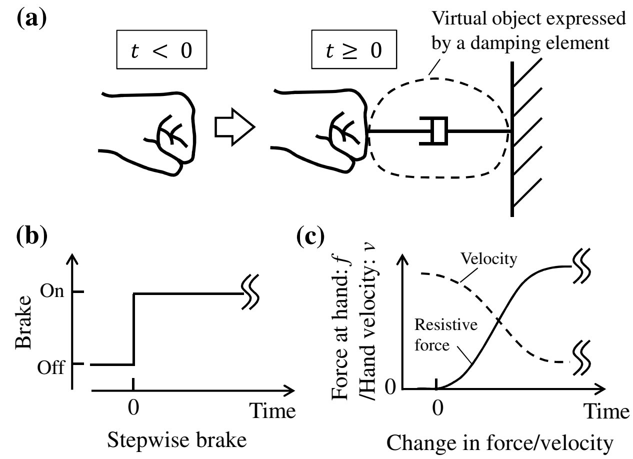


Fig. 4 Stepwise brake that achieves physically maximum impact. **a** Process of collision with a virtual object expressed by a damping element. **b** Operation of the stepwise brake. **c** Change in force and velocity caused by the stepwise brake. $t = 0$ signifies the time at the moment of impact

3 Methods

We previously discovered that a pulsive brake that momentarily releases the brake immediately after a collision can deliver greater impact perception than a stepwise brake (Okada et al. 2016a, b). As shown in Fig. 5b, releasing the brake leads to a transient drop of resistive force and a transient rise of hand velocity. Thus, in the pulsive brake, the impulse applied toward the operator is smaller than that in the stepwise brake. This suggests that the impact perception is disparate from physical aspects. In our previous experiment, only two types of pulsive brakes were used and the mechanism of impact perception was not discussed. In this study, we varied the number and duration of the pulse brakes as well as the release time of the brake, and quantitatively compared the perceived impact between these pulsive brakes.

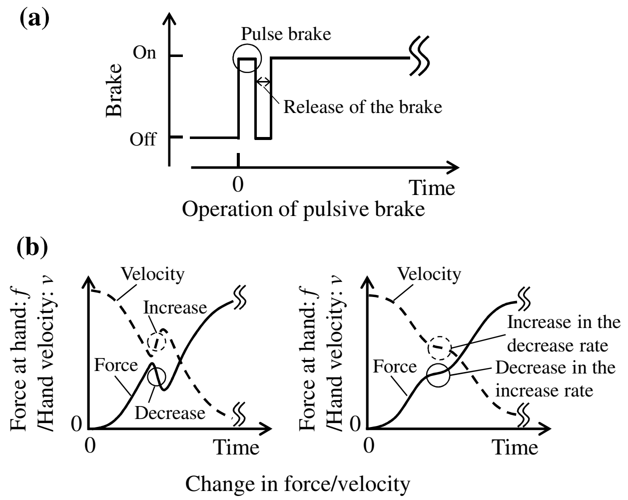
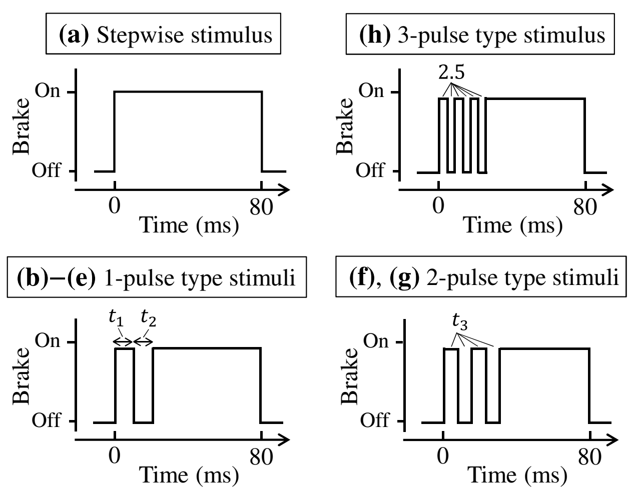


Fig. 5 Pulsive brake that instantaneously releases the brake immediately after impact. **a** Braking operation for the pulsive brake. **b** Change in force and velocity caused by the pulsive brake. Releasing of the brake causes a decrease in force or increase in velocity (left side) and reduction in the rate of increase of force or increase in the rate of decrease in velocity (right side)



Stimuli	t_1 (ms)	t_2 (ms)
(b)	3	3
(c)	5	5
(d)	6	6
(e)	9	3

Stimuli	t_3 (ms)
(f)	3
(g)	4

Fig. 6 Brake operations for eight types of impact stimuli (**a**)–(**h**)

3.1 Impact stimuli

Eight types of impact stimuli were compared in this experiment. Figure 6 shows the brake operations for each impact stimulus. Stimulus (a) was a stepwise brake that continuously activated the brake for 80 ms, which led to the physically maximum impact. Stimuli (b)–(h) included one or more pulse brakes generated by releasing of the brake before the main stepwise brake. Stimuli (b)–(e) included one pulsive brake. For instance, in stimulus (b), the first brake duration lasted 3 ms, followed by releasing of the brake for 3 ms, and then presentation of the main brake. For the stimuli that had more than two pulse brakes, presentation and release of the brake were repeated at a certain period. Stimuli (f) and (g) had two pulse brakes each presented with a period of 6 ms and 8 ms. Stimulus (h) had three pulse brakes presented with a period of 5 ms. We unified the total duration of every stimulus to 80 ms.

The duration and intervals of the pulse brakes were devised from trial and error. When the release time of the brake is overly long, either impact perception occurs multiple times or the system vibrates. Such stimuli are qualitatively different from a step-wise brake. Hence, we limited the release time of the brake to less than 6 ms, with which such sensations were not evoked. In addition, when the time from the start of the stimulus to the main brake is overly long, such stimuli provide an apparently different sensation from the impact,[1] which is an instantaneous event caused by a collision with an object. Thus, we regulated the time by the main brake to less than 16 ms. The seven types of pulsive brakes were designed to show variation under these regulations. Note that these specifications depend on the experimental apparatus, as discussed in Sect. 7.4.

3.2 Participants

Thirteen naive participants (11 males and 2 females; all right-handed) took part in the experiment. We obtained informed consent from all participants before the experiment.

3.3 Experimental procedure

In the experiment, we investigated the impact stimuli that delivered large impact perception based on Scheffe's paired comparison method (Scheffe 1952). In each trial, the participants compared a pair of stimuli (stimulus X, stimulus Y) in terms of the magnitude of perceived impact on five scales, from −2 (larger in X) to 2 (larger in Y). The participants could experience each stimulus as many times as they desired during the experiment. Typically, they experienced each stimulus three or four times before making a judgment. The contact force and hand velocity during the last impact experienced for each stimulus were automatically recorded and used for subsequent analysis. Each participant evaluated

[1] For example, some feel a moderate collision with a deformable object.

${}_8P_7 = 56$ pairs, which is the number of all possible combinations of the stimuli in the case where the order of the stimuli (which stimulus is labeled as X (or Y)) is considered. We divided the experiment into two sessions, with both sessions having 28 paired stimuli randomly presented. A break of a few minutes was given between sessions.

Through preliminary experiments, it was found that when the collision speed of the crank at the 90 deg point was slow, the difference between the stimuli was vague. Therefore, in the present experiment, we regulated the collision speed of the crank to faster than 10 rad/s and did not start the stimuli when the collision speed fell below the limit. Note that the minimum collision speed for discerning the stimuli is unknown. Participants had a few minutes to be familiar with this speed condition beforehand. The average collision speed was in the range 10.8–18.3 rad/s for all participants in the main tasks. The stimuli were presented virtually every time despite this regulation.

4 Physical indices for impact perception

In this study, we also aimed to investigate a physical index consistent with the impact perception. For this purpose, we measured contact force and hand velocity during a collision and extracted some feature physical quantities from the data. Then, we investigated correlations between the physical quantities and the impact perception obtained in the psychophysical experiment.

4.1 Proposition: absolute change of resistive force or velocity affects impact perception

We propose, as an index of impact perception, physical quantities relating to the change in contact force and the change in hand velocity just after the impact on the basis of the studies about presentation of hardness by using haptic interfaces.

In order to improve the sensation of hardness perceived from virtual objects by using haptic interfaces wherein the output force is limited, increasing the rate of the force output just after contact is effective (Lawrence et al. 2000; Han and Choi 2010; Hauser and Gerling 2018). In the case of impact perceived from collision with an object, it is also expected that the greater the force applied in a short period, the greater the perceived impact. For presenting impact using a brake, continuous operation of the brake after the collision maximizes the increasing rate of the force. Thus, the stepwise brake appears to be the best method to deliver large impacts. In the previous experiment (Okada et al. 2016a, b), however, a pulsive brake, in which resistive force momentarily decreased after the collision, delivered a larger perceived impact than the stepwise brake. If the enhancement of impact perception is not caused by increasing the rate of force itself but rather changing rate of force, the force does not have to necessarily continue to increase. Hence, we investigated whether the absolute change of force, which includes decreasing the force too, affects perceived impact. This cumulative absolute change of force is expressed as follows:

$$J_{|\dot{f}|}(\Delta t) = \int_0^{\Delta t} |\dot{f}(t)| \mathrm{d}t. \tag{2}$$

Here, $f(t)$ represents the contact force at hand after t ms from a collision. The unit of Δt is ms.

Applying a large momentum to the operator at the moment of collision is effective for presenting a large impact, by using active-type haptic interfaces (Vander Poorten and Yokokohji 2007). On the other hand, passive haptic interfaces present impact by using resistive force and deriving momentum from the operator because they cannot generate momentum independently. Assuming that deriving the operator's momentum in a short period induces great impact perception, continuously functioning the stepwise brake from the moment of collision should present the maximum impact. This is because the decreasing rate of hand velocity, i.e., that of momentum of the hand, becomes maximum for a stepwise brake as shown in Fig. 4. However, a pulsive brake, wherein the hand velocity momentarily increases just after a collision, as shown in Fig. 5b (left), induced a larger impact than the stepwise brake in our previous experiment (Okada et al. 2016a, b). This result indicates the possibility that an abrupt increase of hand velocity caused by instantaneous release of the brake contributes to the impact perception. Once the brake is instantaneously released just after a collision, the operator's hand is accelerated by their own output force being generated against the resistive force of the brake. Hence, passive haptic interfaces can also realize the process, in which momentum abruptly increases, by using the pulsive brake. Then, we hypothesize that the perceived impact is enhanced by the following phenomena: an abrupt decrease in momentum caused by the resisting hand movement, and an abrupt increase of momentum owing to the momentary release of the resistive force. Based on this hypothesis, we propose, as an index of perceived impact, the integral of absolute change of the hand velocity immediately after the collision, which is defined as follows:

$$J_{|\dot{v}|}(\Delta t) = \int_0^{\Delta t} |\dot{v}(t)| \mathrm{d}t. \tag{3}$$

Here, $v(t)$ represents the hand velocity after t ms following the collision.

4.2 Physical indices for magnitude of impact

We investigated the following physical quantities representing the physical magnitude of impact as candidates for a physical index consistent with the human impact perception in addition to $J_{|\dot{f}|}(\Delta t)$ and $J_{|\dot{v}|}(\Delta t)$.

- Maximum force value, $f_{\max}$
- Time taken for the force to reach its maximum value, $t_{\max}$
- Minimum velocity value, $v_{\min}$
- Time taken for velocity to reach its minimum value, $t_{\min}$
- Resistive force after Δt ms from the collision, $f(\Delta t)$ (increase of force)
- Decrease in velocity during Δt ms from the collision, $v_d(\Delta t)$
- Impulse during Δt ms from the collision, $I(\Delta t)$
- Energy consumption during Δt ms from the collision, $E(\Delta t)$

$v_d(\Delta t)$, $I(\Delta t)$, and $E(\Delta t)$ are defined as follows, respectively:

$$v_d(\Delta t) = v(0) - v(\Delta t), \tag{4}$$

$$I(\Delta t) = \int_0^{\Delta t} f(t)\mathrm{d}t, \tag{5}$$

$$E(\Delta t) = \int_0^{\Delta t} f(t)v(t)\mathrm{d}t. \tag{6}$$

In the event that the contact force monotonically increases during Δt ms from the collision, $I(\Delta t)$ is an identical index to $J_{|\dot{f}|}(\Delta t)$. The decrease in momentum during Δt ms from the moment of collision can be expressed by using hand mass m and hand velocity v as follows:

$$m(v(0) - v(\Delta t)) = mv_d(\Delta t). \tag{7}$$

Therefore, given that the hand mass is constant, the decrease in velocity $v_d(\Delta t)$ is an qualitatively identical index to the decrease in momentum.

5 Results

5.1 Collision speed for each stimulus

The mean collision speed for the eight types of stimuli was 11.2 rad/s; it did not statistically differ among the stimuli types (ANOVA, $F(7, 96) = 1.89$, $p = 0.080$). For this computation, we computed the mean collision speeds for individual participants, i.e., 104 (13 participants × 8 stimuli) mean values were used for the statistic test. Nonetheless, we found that the collision speeds for stimuli (f) (11.5 ± 3.0 rad/s, mean and standard deviation) and (h) (11.4 ± 2.8 rad/s) tended to be greater than the others. As described later, these two types of stimuli were perceived as weaker than the others. Hence, for clearly feeling the impacts, the participants might have collided with these stimuli at speeds faster than those for the other types of stimuli. The stimuli (a) (10.8 ± 1.7 rad/s) and (e) (10.8 ± 1.8 rad/s) recorded the smallest collision speeds.

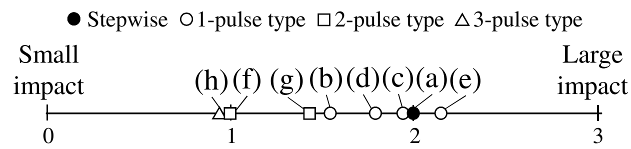


Fig. 7 Psychophysical scale of the impact stimuli

5.2 Perceived impact

Following Scheffe's method (Scheffe 1952), the scores of stimuli were calculated within individual participants. For example, in a trial, when stimulus X was judged substantially greater than stimulus Y, 2 points were assigned to stimulus X. The scores were then accumulated among trials; based on these scores, the stimuli were then ranked. In the case of a tie rank, the average ranks were assigned. Table 1 shows the ranking of the scores of stimuli for each participant. Stimulus (e) had the highest total rank, followed by stimulus (c) as the second highest, and stepwise stimulus (a) as the third highest. The ranks of the eight types of stimuli differed significantly (Friedman test, $\chi^2(7) = 58.76, p < 0.01$). The question is whether stimuli (c) and (e) were felt greater than stimulus (a). Hence, as post hoc tests without p value correction, we compared stimuli (a) and (e) and stimuli (a) and (c), with the result showing that there was a significant difference between stimuli (a) and (e) (Friedman test, $\chi^2(1) = 8.33$, $p = 0.0038$), whereas there was not a difference between stimuli (a) and (c) ($\chi^2(1) = 1.0$, $p = 0.31$). This indicates that stimulus (e) delivered a larger impact perception than the stepwise brake (a), which achieved the physically maximum impact.

In the later analysis, to compare some physical indices of brake stimuli, which are ratio scales and impact perception, we converted the above results into psychophysical scales (Scheffe 1952), which can be treated as interval scales. Figure 7 shows the psychophysical scales of the stimuli obtained from the results for all participants. The larger the psychophysical scale of a stimulus, the greater the impact perception the stimulus presented. Stimulus (e) had a larger psychophysical scale than the stepwise stimulus (a). There was a tendency for the lower number of pulse brakes delivered

Table 1 Rank of the eight types of impact stimuli by individual participants. The total rank at the bottom was obtained by ranking the rank sum among all participants for each stimulus

Participants	Ranking							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
A	5	1	3	6	4	7	2	8
B	4	6	1.5	3	1.5	8	5	7
C	5	3	4	1.5	1.5	7	6	8
D	5	3	4	1.5	1.5	7	6	8
E	1.5	4	1.5	6.5	3	6.5	5	8
F	3.5	7.5	3.5	5	1	7.5	2	6
G	2	4	1	5	3	8	6	7
H	3.5	3.5	5	2	1	8	6	7
I	2	4	1	5	3	8	6	7
J	1	5	3	4	2	7	6	8
K	3	6.5	4	2	1	8	5	6.5
L	6	4	2.5	2.5	1	5	7	8
M	3	6	4.5	4.5	1	8	2	7
Total	3	5	2	4	1	7	6	8

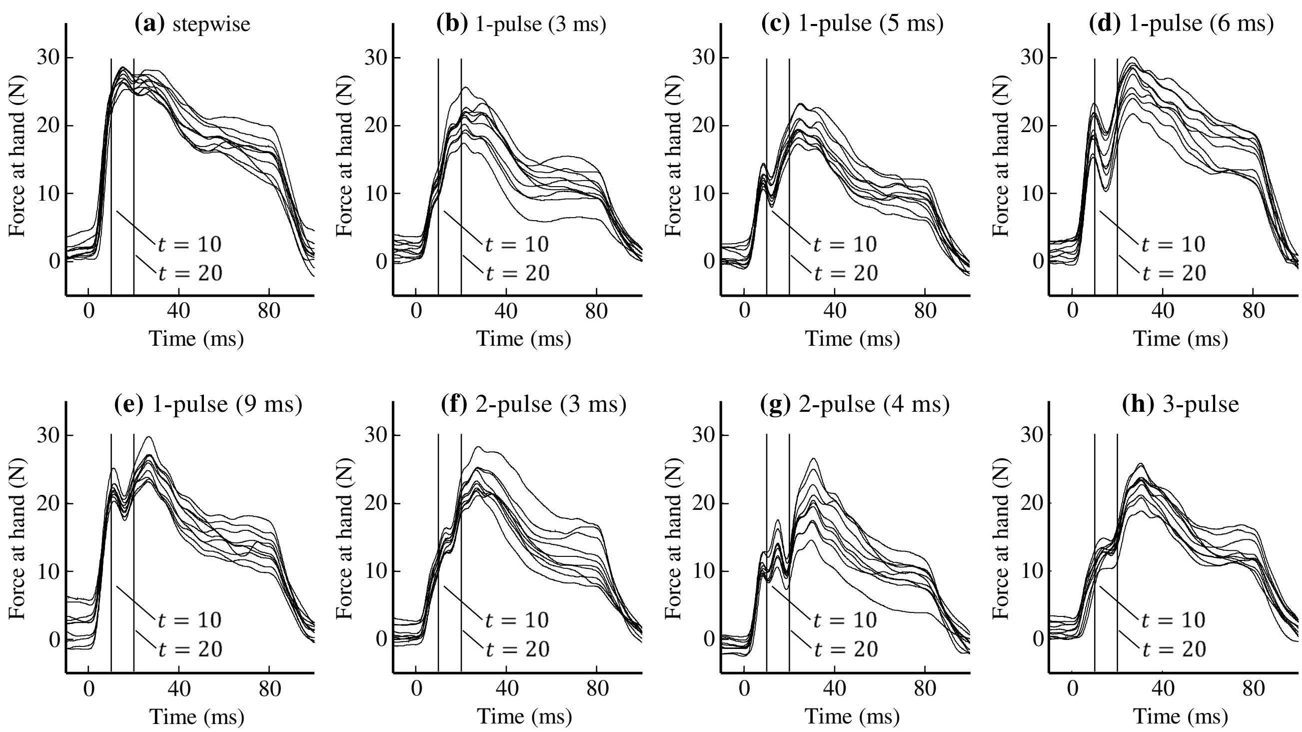


Fig. 8 Examples of force at the hand for eight types of impact stimuli (**a**)–(**h**). Each stimulus started at $t = 0$. The collision speed in each case was in the range of 10–11 rad/s. Ten samples are displayed for each stimulus

to result in the greater impact perception. We utilize these continuous scales in after-mentioned correlation analysis.

5.3 Correlation between physical indices and impact perception

Figures 8 and 9 show, for each stimulus, the examples of changes in the contact force at the operator's hand during collision measured by the force sensor and examples of changes in the hand velocity during collision calculated from the measurements recorded by the encoder. $t = 0$ is the time at the moment of collision. For stepwise stimulus (a), the contact force abruptly increased immediately after the collision, and moderately decreased after the force reached its peak. The hand velocity abruptly decreased immediately after the collision, and then moderately decreased.

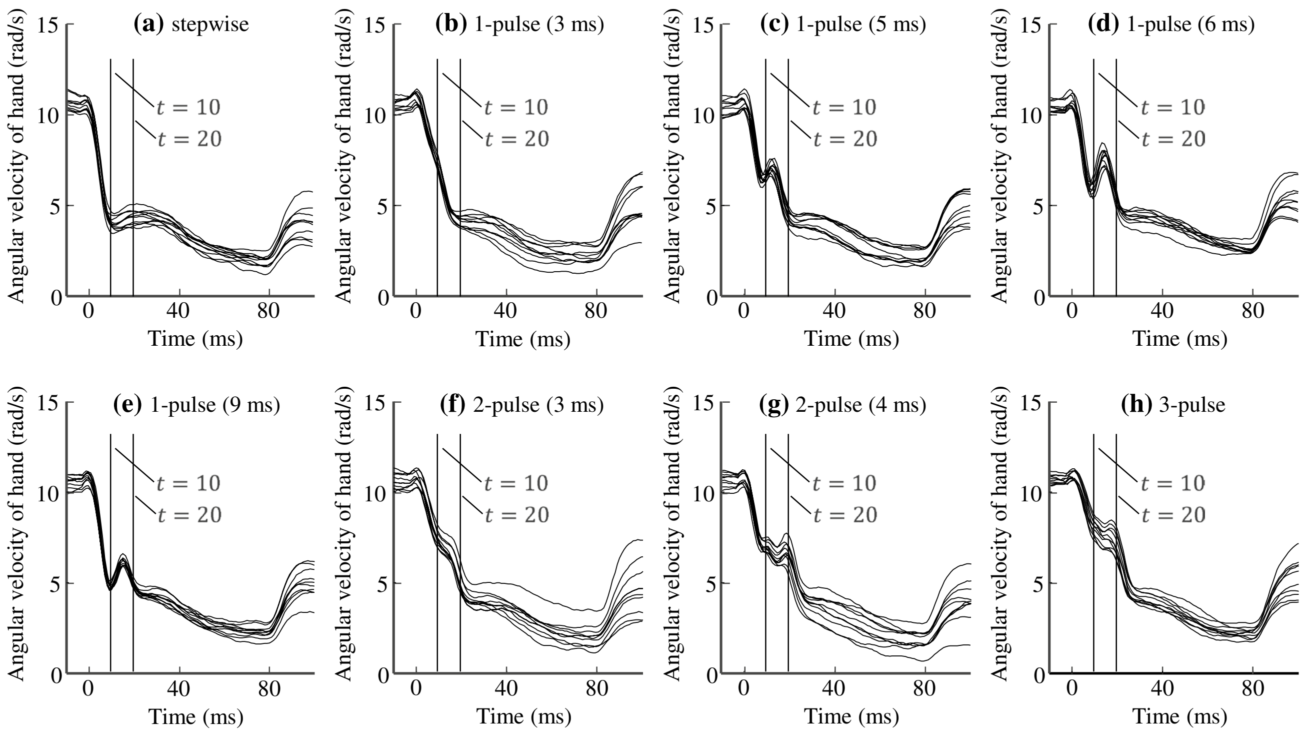


Fig. 9 Examples of angular velocity of the hand for eight types of impact stimuli (**a**)–(**h**). Each stimulus started at $t = 0$. The collision speed in each case was in the range of 10–11 rad/s. Ten samples are displayed for each stimulus

Table 2 Correlation coefficients R between physical indices and psychophysical scale of the impact stimuli. Computed by the samples with the collision speeds of 10–11 rad/s

f_{max}	t_{max}	v_{min}	t_{min}	Δt	$I(\Delta t)$	$E(\Delta t)$	$f(\Delta t)$	$v_d(\Delta t)$	$J_{\lvert\dot{f}\rvert}(\Delta t)$	$J_{\lvert\dot{v}\rvert}(\Delta t)$
0.49	0.39	0.09	0.03	5 ms	0.61	0.12	0.60	0.66	0.61	0.60
				10 ms	0.62	0.37	0.70	0.84	0.76	0.91
				15 ms	0.63	0.32	0.47	0.34	0.80	0.92
				20 ms	0.62	0.31	0.48	0.46	0.72	0.78
				25 ms	0.61	0.26	0.28	0.00	0.50	0.60
				30 ms	0.56	0.25	0.00	0.24	0.46	0.54

For pulsive stimuli, the contact force and the hand velocity fluctuated because of releases of the brake. The stimuli with the longer release time of the brake and with the later timing of the first release of the brake tended to show the greater changes in force and velocity when the brake was released. Specifically, for stimuli (c), (d), (e), and (g), decreases in the force and increases in the velocity were observed when the brake was released, as shown in Fig. 5b (left). On the other hand, for stimuli (b), (f), and (h), decreases in the increase rate of force and increases in the decrease rate of velocity were observed, as shown in Fig. 5b (right).

The physical quantities introduced in Sects. 4.1 and 4.2 were calculated for the 192 samples (at least 12 repetitions for each stimulus) that had collision speeds of 10–11 rad/s. The recorded examples are shown in Figs. 8 and 9 . Note that the physical indices should not be compared among substantially different collision speeds because of the nature of a damping brake. The physical quantities expressed in the form of integration were calculated for different integral values of Δt from 5 ms to 80 ms with 5 ms increments. Table 2 shows the correlation coefficients between the physical quantities that were computed using the samples of 10–11 rad/s and the psychophysical scale of impact perception. For the physical quantities expressed as functions of Δt, only the results for $\Delta t \leq 30$ ms are shown because the correlations with the impact perception were small for $\Delta t > 30$ ms. The correlation with the impact perception was the largest for $J_{|\dot{v}|}(15)$ with $R = 0.92$ followed by $J_{|\dot{v}|}(10)$ with 0.91, $v_d(10)$ with 0.84 and $J_{|\dot{f}|}(15)$ with 0.80. Figure 10 shows the relationships between the psychophysical scales and $J_{|\dot{v}|}(15)$ and $v_d(10)$. The correlation coefficients for f_{max}, t_{max}, v_{min}, and t_{min}, relating to the peak values of force or velocity, were below 0.5. The correlation coefficients for energy consumption expressed as temporal integration of the

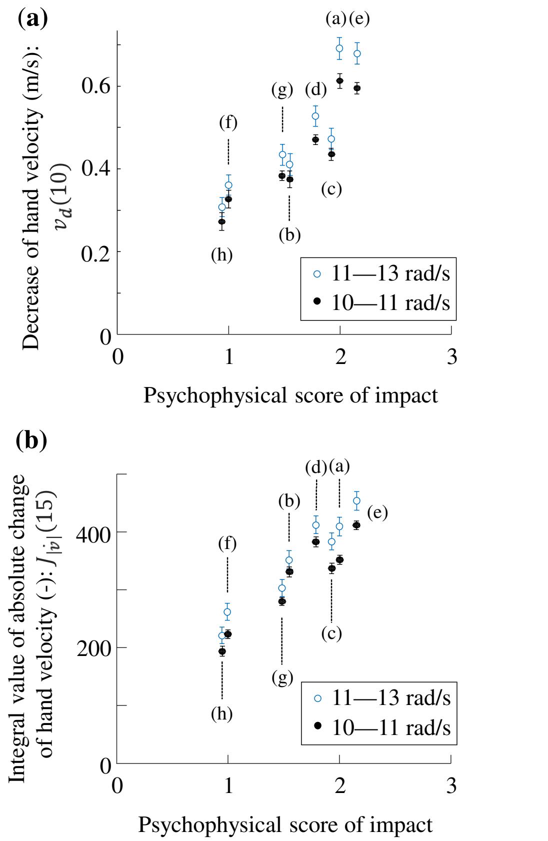


Fig. 10 Relationship between the observed psychophysical scale of the stimuli and physical indices for perceived impact. **a** Decrease in hand velocity for $\Delta t = 10$ ms: $v_d(10)$. **b** Integral value of absolute change of hand velocity for 15 ms: $J_{|\dot{v}|}(15)$. Each dot shows the mean value of the index among samples for each stimulus (**a**–**h**) with standard deviation. Filled and open circles are for the collision velocities of 10–11 rad/s and 11–13 rad/s, respectively. For the computation of open circles, 150 samples whose collision speeds were in the range of 11–13 rad/s were used

product of contact force and hand velocity were all below 0.4.

Among the physical quantities that we investigated, the physical quantity that showed the largest correlation with the impact perception was neither the maximum value of the force, the impulse, nor the change of momentum; it was the integral of the absolute change of velocity. Thus, in the case of presenting impact by using a passive haptic interface, large impact perception might be delivered by momentarily breaking off the resistance just after a collision, which causes absolute change of momentum due to the acceleration and deceleration of the hand. The correlation coefficients for energy consumption were smaller than those for other physical quantities, including force only or velocity only, indicating that when perceiving impact, we utilize force or velocity alone, or their linear combination, rather than the interaction between them.

6 Follow-up study

Stimulus (e) was judged as the greatest impact in the aforementioned experiment. One question is whether there exist stimuli that present the impact greater than stimulus (e). Assuming that such stimuli may exist in the vicinity of stimulus (e), we newly prepared for five one-pulse stimuli that were close to stimulus (e) of which $(t_1, t_2) = (9, 3)$. These stimuli (i)–(m) were $(t_1, t_2) = (9, 5)$, (11,3), (7,3), (10,4), and (8,2). By using these five types of stimuli, step-wise stimulus (a), and stimulus (e), we performed a paired-comparison test. The experimental procedures were same as those in Sect. 3. For this experiment, 10 males (right-handed) were invited. Four of them participated in the experiments in Sect. 3.

Table 3 shows the ranks assigned by individual participants. Stimulus (i) exhibited the highest rank, followed by

Table 3 Rank of the seven types of impact stimuli used in the follow-up experiment. The total rank at the bottom was obtained by ranking the rank sum among all participants for each stimulus

Participants	Ranking						
	(a)	(e)	(i)	(j)	(k)	(l)	(m)
A	3	2	1	4.5	7	4.5	6
C	6	1.5	1.5	7	4	3	5
E	3	2	1	4.5	6	4.5	7
F	5	1	4	6	3	2	7
O	6	2	3	7	1	4	5
P	3	1	2	5.5	7	4	5.5
Q	4	3	1	5	6	2	4
R	2.5	2.5	4	6	7	1	5
S	3	4	1	5.5	5.5	2	7
T	3	1.5	1.5	7	4.5	4.5	6
Total	4	2	1	7	5	3	6

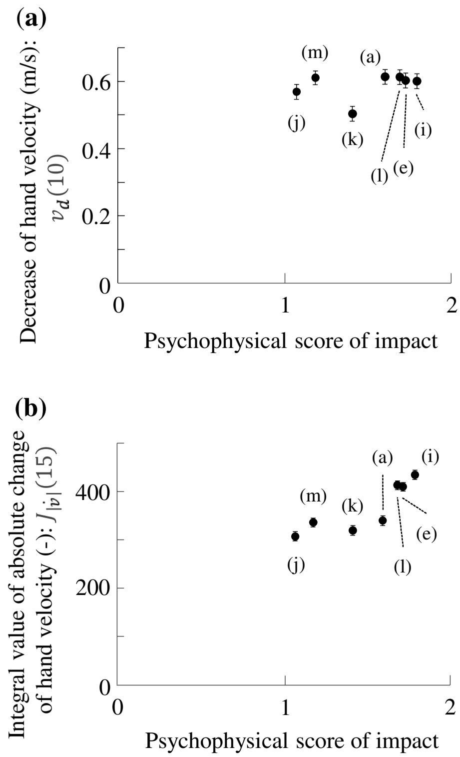


Fig. 11 Psychophysical scores and physical indices for perceived impact (mean and standard deviations) in the follow-up study. **a** Decrease in hand velocity at $t = 10$ ms: $v_d(10)$. **b** Integral value of absolute change of hand velocity for 15 ms: $J_{|\dot{v}|(15)}$

(e), (l), (a), (k), (j), and (m). Significant differences were found among the seven types of stimuli ($\chi^2(6) = 36.64$, $p < 0.001$, Friedman test). As post hoc tests without p values correction, we compared step-wise stimulus (a) and stimuli (i), (e), and (l), which were ranked higher than stimulus (a). The ranks of stimuli (i) and (e) were higher than those for step-wise stimulus (a) ((i) versus (a): $\chi^2(1) = 6.4$, $p = 0.011$, (e) versus (a): $\chi^2(1) = 5.4$, $p = 0.020$). Stimuli (l) and (a) did not exhibit significant differences ($\chi^2(1) = 0.4$, $p = 0.53$). There were no significant differences among stimuli (i), (l), and (e) ((i) versus (l): $\chi^2(1) = 3.6$, $p = 0.058$, (i) versus (e): $\chi^2(1) = 0$, $p = 1.00$, (l) versus (e): $\chi^2(1) = 1.6$, $p = 0.21$).

On the basis of these results and analyses, stimulus (i) was found to present an equally large impact as stimulus (e) and both of them yielded greater impact perception than stimulus (a). Nonetheless, the stimuli that yield a statistically greater impact perception than stimulus (e) were not found.

Similar to Sect. 5, we computed $v_d(10)$ and $J_(|\dot{v}|)(15)$ for these stimuli. For the computation, we used 145 trials, of which collision speeds were 10–11 rad/s including at least 12 stimuli for each type of stimulus. Figure 11 shows the relationships between these two types of indices and the psychophysical scores of seven types of stimuli. Note that these psychophysical scores are not directly compatible with those computed in Sect. 5 because the stimulus set used in the experiments were different between two experiments. Unlike previous experiment, $v_d(10)$ did not exhibit a strong correlation with the psychophysical scores ($R = 0.34$). $v_d(10)$ is the decrease in the hand velocity at $t = 10$ ms, and the seven types of stimuli did not substantially vary except for stimulus (k). This is reasonable because the relies of the brake started at 7–11 ms for the six types of one-pulse stimuli and they did not produce substantial differences before 10 ms. In contrast, $J_{(|\dot{v}|)}(15)$ and the psychophysical scores exhibited a higher correlation ($R = 0.86$) because it covers the hand velocity until 15 ms.

7 Discussion

7.1 Similarity between impact and hardness perception

For presentation of hardness by using active-type haptic interfaces, a rapid increase of contact force just after a collision is more important than the maximum value of the force (Lawrence et al. 2000; Han and Choi 2010; Hauser and Gerling 2018), which is consistent with the results of the present study. In this experiment, $f(5)$ and $f(10)$, representing the increase of the force just after the collision, showed higher correlations with the impact perception than f_{max} and t_{max}, which pertain to the peak values of the force. Moreover, it is also true that a decrease in hand velocity, $v_d(5)$ and $v_d(10)$, immediately after the collision showed higher correlations with the impact perception than v_{min} and t_{min}, which pertain to the peak values. These results indicate that for presenting impact with passive haptic interfaces, the change rates of force and velocity just after a collision are more important than their peak values.

These results may be related to the time that elapses before each physical quantity is observed after the collision. Not only in $f(\Delta t)$ and $v_d(\Delta t)$, but also in the other physical quantities expressed as functions of Δt, there were trends in which the correlation coefficient was largest for Δt below 20 ms and was smaller for the greater Δt. On the other hand, the physical quantities pertaining to the peak values of force and velocity that had small correlation coefficients were recorded after the point in time when some indices with high correlation coefficients were recorded. As shown in Figs. 8 and 9 , the peaks of the force were observed typically at around 30 ms from the time of collision and those of the velocity were typically observed at around 80 ms in most trials. Thus, the magnitude of the impact presented by using a passive haptic interface can be judged using the information obtained before the force and the velocity reach their peaks.

7.2 Change of force/velocity versus integral of absolute change of force/velocity

Under the condition that Δt is larger than 5 ms, the correlation with the impact perception was higher for $J_{|\dot{f}|}(\Delta t)$ than for $f(\Delta t)$, and higher for $J_{|\dot{v}|}(\Delta t)$ than for $v_d(\Delta t)$. These results support the propositions in Sect. 4.1.

$f(\Delta t)$ and $J_{|\dot{f}|}(\Delta t)$ showed differing correlation coefficients especially after 10 ms, because the contact force turned downward as a result of the pulse brakes for many pulsive stimuli. Hence, in cases where the force decreases because of the pulse brake, the absolute change of force may explain the impact perception more than the increase of force. This suggests the possibility that not only the increase in force but also the decrease in force contribute to the enhancement of impact perception.

Comparing $v_d(\Delta t)$ and $J_{|\dot{v}|}(\Delta t)$ in the same manner, these indices also showed large differences in correlation coefficients after 10 ms when the effects of the pulse brakes appeared. The high correlations between $J_{|\dot{v}|}(\Delta t)$ and the impact perception also support the same postulate.

Figure 10a, b shows the values of both indices for each stimulus. The results for $v_d(10)$ and $J_{|\dot{v}|}(15)$ are shown as they exhibited the largest correlation coefficients with the impact perception among different Δt values. The decrease in hand velocity $v_d(10)$ was the largest for stimulus (a) because continuous functioning of the brake maximizes the impulse to the hand. For the same reason, the earlier release of the brake tended to lead to a smaller $v_d(10)$ value. On the other hand, the integral value of the absolute change of velocity was the largest for stimulus (e), which induced the maximum impact perception in the experiment. In Fig. 9, for step stimulus (a), the hand velocity moderately changed after the velocity reached its local minimum value around 10 ms after the collision; on the other hand, for stimulus (e), abrupt changes in velocity continued owing to pulse brakes, resulting in the large values of $J_{|\dot{v}|}(15)$. Moreover, the pulsive stimuli having more than two pulse brakes (stimuli (f), (g), and (h)) showed little changes in velocity because the timings of the on and off switching of the brake were so quick that the hand velocity lagged behind.

7.3 What affects perceived impact?

We theorize that $J_{|\dot{v}|}(10)$ or $J_{|\dot{v}|}(15)$, which show high correlations with the impact perception ($R > 0.9$ or 0.86), can be effective indices in stimulus deign for presenting impact via passive haptic interfaces. However, there is no evidence to conclude that humans actually perceive impact from these physical quantities. In fact, although stimulus (d) was perceived as having the fourth largest impact in the experiment, it took the second largest values for $J_{|\dot{v}|}(15)$, next to stimulus (e) in Fig. 10, showing an inconsistency with the experimental results. Following our intuition, it is also unlikely that humans judge the magnitude of impact by using only information for a short period of 10–15 ms after the collision. In reality, humans may use broader information in terms of time: in order to judge the magnitude of an impact, humans probably analyze information until the contact force reaches its peak.

One speculation of the effects of pulsive brakes is that the intermittent braking effectively stimulates sensory organs. Presenting pulse brakes just after the collision, the muscles of the arm and finger and the tendons extend or contract with acceleration and deceleration of the hand. This may result in repeated activations of mechanoreceptors in the flexor and extensor muscles and tendons in a short period, thus contributing to greater impact perception. Muscle spindles could have responded to braking pulses used in the experiments considering their response characteristics (Burke et al. 1976). A possible reason why the correlation with the impact perception is larger for $J_{|\dot{v}|}(\Delta t)$ than for $J_{|\dot{f}|}(\Delta t)$ is that the changes in hand velocity more directly relate to the extension and contraction of the arm and finger than that in the contact force. Nevertheless, there is no physiological evidence that a rapid change in force caused such activation of muscles in our study.

Another speculation is based on the fact that actual collision produces high-frequency components. The presentation of high-frequency component at the moment of collision with virtual objects increases the experienced realism or hardness (Wellman and Howe 1995; Okamura et al. 2001; Hwang et al. 2004; Kuchenbecker et al. 2006; Fiene and Kuchenbecker 2007; Higashi et al. 2016, 2018, 2019; Culbertson and Kuchenbecker 2017). The neural basis of this effect is unclear; however, humans know that the natural frequencies of stiffer objects are generally higher and our daily experiences may underlie this effect. Nonetheless, it is difficult to pursue this effect by using our experimental setup. For passive haptic interfaces, the higher the frequency of the pulse brakes, the smaller the changes in force and velocity. Consequently, comparing the effects of different frequency components while maintaining the changes in force and velocity is difficult. Moreover, some stimuli having a single pulse are not suitable for frequency analysis. From the above, in order to discuss the effects of frequency of stimuli on the impact perception, we need to use active haptic interfaces and fairly compare different frequency contents. As the objective of this research is to investigate the impact perception presented by passive haptic interfaces, we refrain from discussing the effects of stimuli frequency in detail here.

7.4 Generality of the study

The generality of the present experiment remains to be studied. Pulsive brakes can also be generated by actuators other than DC motors; however, it is not clear whether the same principle holds for those other actuators and therefore should be investigated in future studies. The temporal characteristics of stimuli are mainly dependent on the time constant and responsivity of the motor used in the experimental apparatus. As aforementioned, the pulsive brakes included a delay of 1–2 ms. Hence, integral intervals of the indices must be changed as needed when using products that show quite different response performances from that of the products we used. In fact, we obtained different experimental results in previous experiments with a different experimental setup (Okada et al. 2016a, b). In the experiment, a 2-pulse type stimulus was perceived as having a larger impact than stepwise and 1-pulse type stimuli. In the experiment, a FET (TB6643KQ, TOSHIBA), showing very high responsivity (below 1 μs), was used as the switch of the short circuit in place of a relay[2]. Furthermore, as aforementioned, the impact is not effectively experienced when the collision speed is small, considering the principle of the damping brake. Hence, the hardware specification including the length of links and gear friction should have some effect on the perception of pulsive brakes. Large gear frictions may mask the damping brake and diminish the effect of the passive brakes.

In summary, when using different experimental setups to present impacts passively, the parameters of the impact stimuli should be designed on the basis of the physical indices of which integral intervals are modified depending on the responsivity performance of the setup.

8 Conclusion

In this study, we investigated the perceptual characteristics of pulsive brakes presented by passive haptic interfaces. The physical index that showed a high correlation with the perceived impact was the integral value of the absolute change of hand velocity, rather than the maximum value of the contact force or its impulse. The rapid change in the hand velocity after the collision was substantially related to the impact perception. This result shows that the temporal increase of hand velocity as well as its decrease caused by a pulse brake just after the collision can also improve the impact perception. The abilities of passive haptic interfaces can be improved more than its physical limits by incorporating human perceptual characteristics with passively presented stimuli. Our findings contribute to the expansion of the range of applications for passive haptic interfaces, which are inherently safe and energy-conservative.

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