Evaluation of physical workload affected by mass and center of mass of head-mounted display

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Takanori Chihara[a,*], Akihiko Seo[b]

[a] *Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan*

[b] *Tokyo Metropolitan University, 6-6 Asahigaoka, Hino, Tokyo 191-0065, Japan*

* Corresponding author's E-mail: chihara@staff.kanazawa-u.ac.jp; Tel: +81-76-234-4666

[b]E-mail: aseo@tmu.ac.jp

Abstract

A head-mounted display (HMD) with inappropriate mass and center of mass (COM) increases the physical workload of HMD users. The aim of this study was to investigate the effects of mass and COM of HMD on physical workload. Twelve subjects participated in this study. The mass and posteroanterior COM position were 0.8, 1.2, or 1.6 kg and –7.0, 0.0, or 7.0 cm, respectively. The subjects gazed at the target objects in four test postures: the neutral, look-up, body-bending, and look-down postures. The normalized joint torques for the neck and the lumbar region were calculated based on the measured segment angles. The results showed that the neck joint torque was significantly affected by mass and COM, and it increased with increase of the mass for all test postures. The COM position that minimized the neck joint torque varied depending on the test postures, and the recommended ranges of COM were identified.

Keywords: Head-mounted display, Biomechanical analysis, Physical workload

1. Introduction[1]

A head-mounted display (HMD) is a head-mounted equipment with an image display monitor, and applied to several fields such as engineering design and aviation. In the engineering design process, for example, HMD is used for providing virtual reality (VR) environment. The use of VR helps the designers in all stages of the design process (i.e., from upstream to downstream) by sharing the detailed images of the final product in the early stage itself (Aromaa and Väänänen, 2016). HMD users move their necks and trunks to secure the field of view to see the virtual objects in various postures. While viewing with an HMD, excessive physical workload may occur in different body parts including the cervical segment due to awkward posture and static posture maintenance (Nichols, 1999). An increase in the mass of HMD and a change in the position of the center of mass (COM) may affect the physical workload of HMD users because they may increase the moment acting on the neck and lumbar joints (Baber el al.; 1999, McCauley-Bell; 2002). In the aviation field, Äng and Harms-Ringdahl (2006) and Van den Oord et al. (2012) reported that helicopter pilots experience neck pain because they routinely wear head-mounted equipments, such as a helmet with night vision goggles. Therefore, the mass and COM of HMD should be determined to consider their effects on the physical workload of HMD users.

Knight and Baber (2007) evaluated the physical workload during a simulated patient treatment with HMD by using the rapid upper limb assessment (RULA; McAtamney and Corlett, 1993), which is an observational method to determine physical workload. A higher RULA score represents a higher physical workload. Their study results showed that wearing an HMD resulted in a significantly high RULA score. Forde et al. (2011) investigated the effects of wearing night vision goggles (NVG) equipped in front of the helmet, on cervical spine load, which was found to increase significantly due to the NVG use. Thuresson et al. (2003) measured the electromyogram (EMG) activity of neck muscles during NVG use in different trunk inclinations and neck flexion angles. The average EMG activity in all posture conditions significantly increased on wearing an NVG. Murray et al. (2016) also reported that the use of NVG increased EMG activity in neck muscles. These studies revealed that a head-mounted equipment increased the physical workload in users; however, they cannot determine recommended ranges of mass and COM of HMD because multiple levels were not provided for the mass and COM in their experiments. Knight and Baber (2004) measured EMG activities of the neck muscles while wearing HMD for gazing at the target object. Their HMD had three levels of weight and counterweight for each weight condition (i.e., six conditions in total). However, the 'with' and 'without' counterweight conditions were implemented in different subject groups, and the quantitative evaluation for the appropriate COM range was not provided.

It is necessary to determine the proper mass and COM of HMD to reduce the physical workload and musculoskeletal disorder risk. Therefore, the objective of this study was to quantitatively evaluate the effects of mass and COM of HMD on the physical workload of HMD users. Approximate functions of the physical workload were predicted as a function of the mass and COM, and their proper ranges were discussed.

2. Materials and Methods

2.1 Subjects

Twelve healthy Japanese subjects (six men and six women) aged between 21 and 24 years participated in this experiment. All subjects were university students, and none had a musculoskeletal disorder. Their mean ± standard deviation stature and body mass were 162.6±9.1 cm and 56.7±10.8 kg, respectively. This experiment was approved by the research safety and ethics committee of the Hino campus of Tokyo Metropolitan University (ID: 109). A written informed consent was obtained from all subjects prior to their inclusion in the study.

2.2 Head-mounted display

Figure 1 shows the HMD used in this experiment. The HMD is prototype model from Canon Inc. (Tokyo, Japan); hence, it is not available in the market. The dimensions of the HMD were W24 × D40 × H28 cm, and its mass and COM of front-back direction were varied by attaching a lead weight. The COMs of the right-left and vertical directions were intermediate and 10 cm below the top of the head, respectively. The horizontal and vertical viewing angles of the HMD were 50° and 31°, respectively.

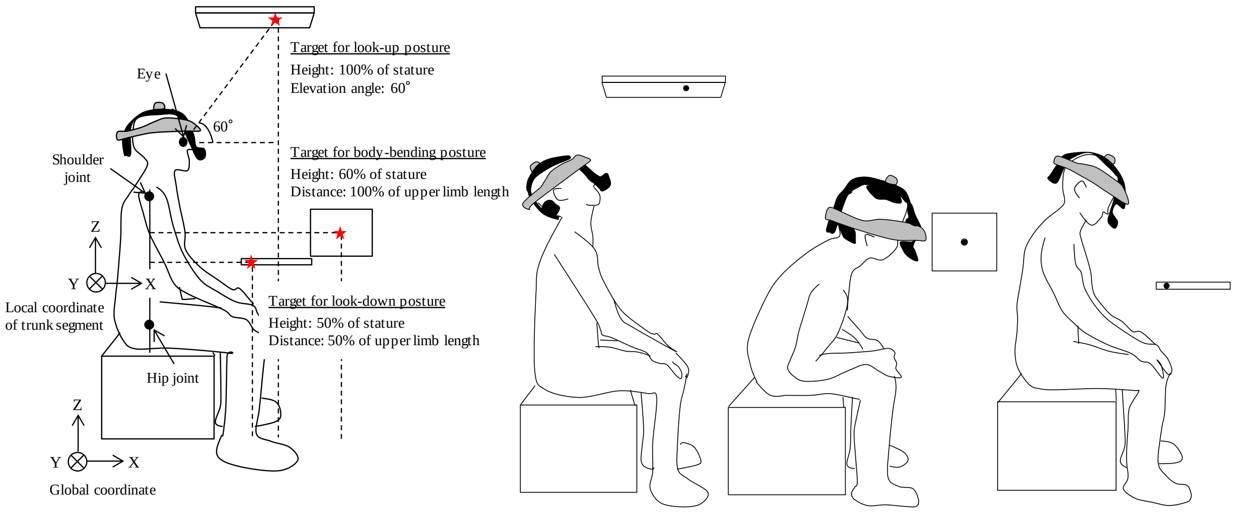
[1] Abbreviations:
VR: virtual reality; HMD: head-mounted display; COM: center of mass; RULA: rapid upper limb assessment; NVG: night vision goggle; EMG: electromyogram; ANOVA: analysis of variance; TNW: total neck workload

Fig. 1 Head-mounted display used in this study (prototype model from Canon Inc., Tokyo, Japan)

2.3 Experimental conditions

The experimental factors were mass (*m*) and COM in the front-back direction (*c*) of the HMD. The mass and COM were 0.8, 1.2, or 1.6 kg and –7.0, 0.0, or 7.0 cm, respectively. Here, the origin of the COM was the top of the head, and positive value represents forward direction. The levels of COM were determined in reference to the COM position of head-mounted equipment used in a previous study (Forde et al., 2011) of which COM was within 7 cm. In addition, it was difficult for our prototype HMD to set the COM more than 7 cm under the constraint of a mass of 0.8 kg because the COM and mass were simultaneously adjusted by attaching a lead weight. Therefore, the absolute value of COM was set less than 7.0 cm. The levels of mass were determined from the constraints of optical equipment that should be installed in the HMD, based on discussion with the manufacturer. For reference, an experiment in which subjects did not wear the HMD was conducted. Therefore, the total number of experimental conditions was 10.

The relationship between the HMD parameters and physical workload may be affected by the posture (Knight and Baber, 2004). Four positions were determined as test postures to cover all possible inclinations while using the HMD: neutral, look-up, body-bending, and look-down. The neutral posture was the reference posture, and the subjects were required to align their trunk straight with the ground and gaze at a target object of 0.5 cm in diameter, which was placed at the eye level of each subject (Fig. 2 (a)). The other three postures (i.e., the look-up, body-bending, and look-down postures) required the subjects to gaze at the target objects in each posture as shown in Fig. 2 (a). In the look-up and look-down postures, the subjects flexed and extended their neck joints to gaze at the target, respectively. In the body-bending posture, the subjects flexed their trunks and gazed at the target from its right side. All positions of the target objects were located in the median sagittal plane of the subjects. The target object for the body-bending posture was placed at the bottom of a cylindrical recess with diameter 2 cm and depth 0.5 cm to control the viewing angle for gazing. The locations of target objects were determined in reference to the cervical range of motion (Wang et al., 2005; Saito et al., 2006).



(a) (b) (c) (d)

Fig. 2 Viewing positions and test postures: (a) viewpoint positions for each test posture and neutral posture (b) look-up posture (c) body-bending posture (d) look-down posture

2.4 Experimental protocol

The subjects sat on a chair while bending their knee joints at a right angle, and were instructed to construct the test postures in the order of neutral, look-up, body-bending, and look-down. They were required to return to the neutral posture before constructing the look-up, body-bending, and look-down postures and hold each test posture for 5 s. The trial was repeated two times sequentially for each HMD condition, with a 3-minute break after each trial. All measurements were performed under ten different HMD conditions in a random order to minimize any complications related to the order of exposure. The subjects were instructed to lightly rest their hands on their knees and to refrain from supporting the weight of the body using their upper limbs.

2.5 Measurements

2.5.1 Joint angles

Three internal measurement unit (Razor IMU, SparkFun Electronics Inc., Boulder, CO, USA) were attached at the head, chest, and lumbar region of each participant. The tilt angles of the sensors were recorded with a sampling rate of 20 Hz. The X, Y, and Z axes of the global and local coordinates corresponded to the forward, leftward, and upward directions of the subjects, respectively. The reference coordinate of the trunk and head segment angles were the global coordinate and local coordinate of the trunk segment, respectively. For the trunk segment, the anterior flexion and right lateral flexion angles were defined as the angles of the Y and X axes, respectively. For the head segment, the anterior flexion, right lateral flexion, and left rotation angles were defined as the angles of the Y, X, and Z axes, respectively.

2.5.2 Joint torque ratios

The outline of joint torque derivation in biomechanical analysis is described as follows using the elbow joint as just an example. Figure 3 shows the two-segment upper limb model, which assumes that the lower arm and the hand are one segment for the purpose of illustration. A torque of amplitude equal to $(M_l L_l + M_o L_o)g$ acts on the elbow joint. To maintain the posture shown in Fig. 3, the elbow joint exerts a torque with the same amplitude but opposite direction to the external torque. This is the joint torque regarded as the indicator of physical workload. Required inputs for the joint torque calculation are as follows: length, mass, and center of mass of each body segment, segment postures, and external forces.

The joint torques of the neck and lumbar region were calculated based on the measured segment angles. The length, mass, and COM of each body segment were quoted from Chaffin et al. (2006) and Ae et al. (1992). These values are provided as ratios against the height and weight of whole body. Subsequently, the calculated joint torques were divided by the maximum joint torque of each joint and for each gender to obtain the joint torque ratio (JTR). The maximum joint torques a human can exert were quoted from Chaffin et al. (2006) and the National Institute of Technology and Evaluation, Japan (2009).

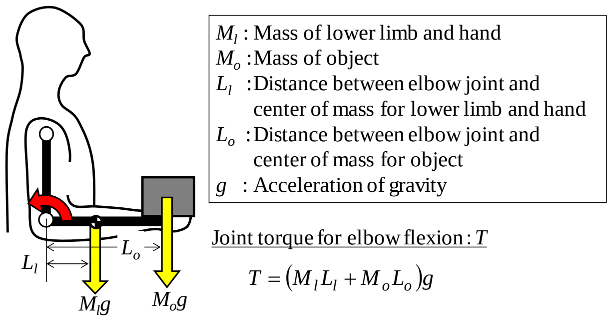


Fig. 3 Two-segment upper limb model and calculation of elbow joint torque

2.5.3 Subjective score

The subjective difficulty in maintaining posture was measured on a scale of 1 to 5, where 1 meant “none” and 5 meant “very severe”. The subjective difficulty was evaluated in comparison with the difficulty in maintaining the neutral posture. Thus, the subjective evaluation was conducted for all test postures except the neutral. The subjective assessment was provided at the end of trial of each HMD condition.

2.6 Analysis

A multi-way analysis of variance (ANOVA) was conducted at 5% significance level to investigate the effects of mass and COM of HMD on the joint angles, JTRs, and subjective scores. The mass and COM were set as control factors and the subject as the block factor. In addition, Tukey’s post-hoc tests were performed to compare the levels of each HMD condition.

3. Results

In this chapter, all figures represent the average values of 12 subjects, and the error bars indicate the standard deviations.

3.1 Joint angles

In this section, only the significant effects of HMD condition on the joint angles are shown.

3.1.1 Neutral posture

The ANOVA results indicated that COM had a significant effect [$F(2, 196) = 5.40$, $p < 0.01$] on the left rotation angle of the head. Figure 4 shows the average left rotation angle of the head. As the result of post-hoc test, the left rotation angle of head for $c = –7.0$ cm was found to be significantly larger than that for the other two COM positions.

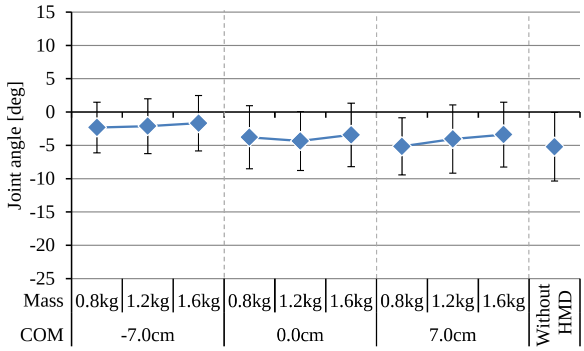


Fig. 4 Left rotation angle of the head in neutral posture

3.1.2 Look-up posture

The ANOVA result shows that the effect of COM was significant for the anterior flexion and left rotation angles of the head ([$F(2, 196) = 7.21$, $p < 0.01$] and [$F(2, 196) = 3.15$, $p < 0.05$], respectively). Figure 5 shows the average anterior flexion and left rotation angles of the head. The anterior flexion angle of the head for $c = –7.0$ cm was significantly smaller than that for $c = 7.0$ cm. For the left rotation angle of the head, the COM had no statistical difference, based on the post-hoc test.

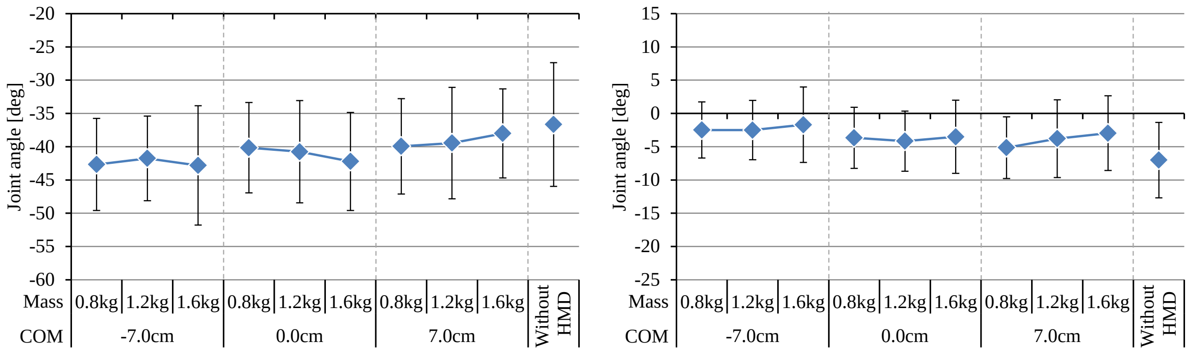


Fig. 5 Joint angles in the look-up posture: (a) anterior flexion angle of the head (b) left rotation angle of head

3.1.3 Body-bending posture

The effects of HMD were significant for the three angles of the head (i.e., the anterior flexion, right lateral flexion, and left rotation angles of the head). Figure 6 shows the three angles of the head. For the anterior flexion angle of the head, the interaction between the mass and COM was significant [$F(4, 196) = 3.92$, $p < 0.01$]. The anterior flexion angle of the head for $c = 7.0$ cm was significantly larger than that for $c = 0.0$ cm when the mass $m = 1.6$ kg. For the right lateral flexion angle of the head, the mass had a significant effect [$F(2, 196) = 6.45$, $p < 0.01$]; and the right lateral flexion angle for $m = 0.8$ kg was significantly larger than that for $m = 1.6$ kg. For the left rotation angle of the head, the COM had a significant effect [$F(2, 196) = 14.9$, $p < 0.01$]; and the left rotation angle for $c = 7.0$ cm was significantly smaller than that for the other two COM positions.

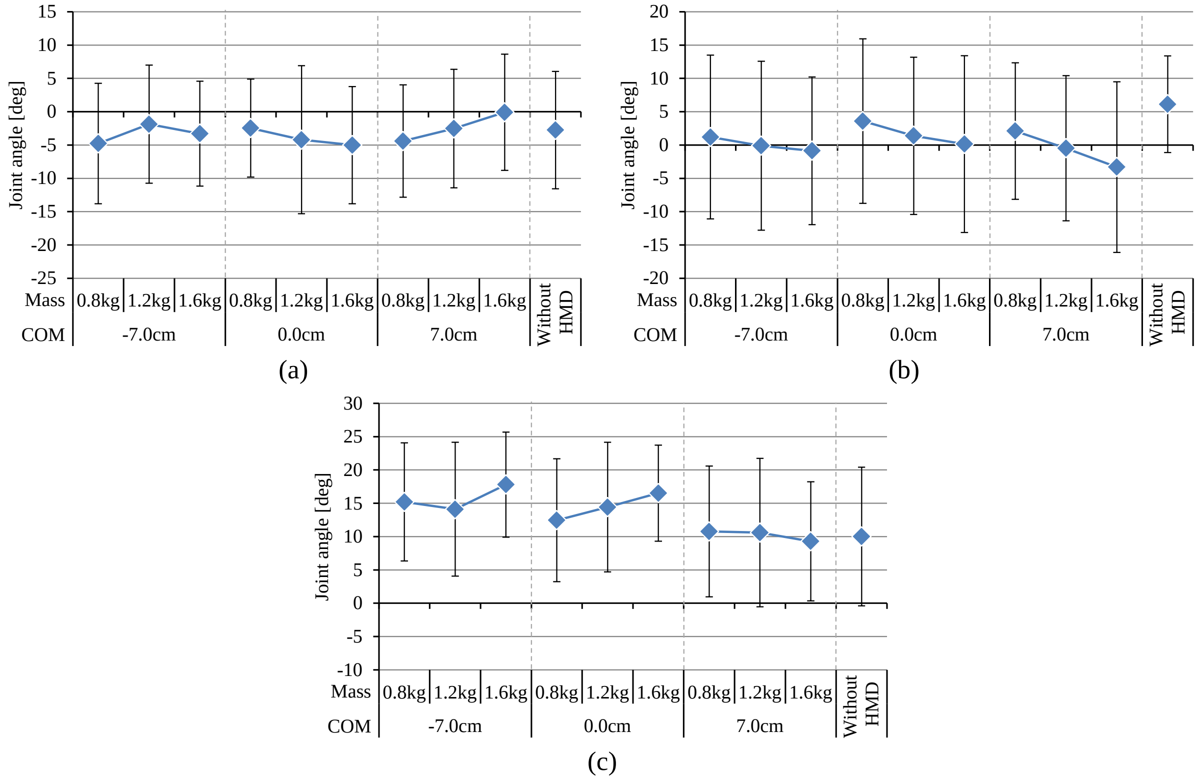


Fig. 6 Joint angles in the body-bending posture: (a) anterior flexion angle of the head (b) right lateral flexion angle of the head (c) left rotation angle of the head

3.1.4 Look-down posture

The ANOVA result shows that the effect of COM was significant for the anterior flexion angle of the trunk and the right lateral flexion angle of the head ([$F(2, 196) = 4.91$, $p < 0.01$] and [$F(2, 196) = 8.85$, $p < 0.01$], respectively). Figure 7 shows the average anterior flexion angle of the trunk and right lateral flexion angle of the head. The anterior flexion angle of the trunk for c = 7.0 cm was significantly larger than that for c = 0.0 cm. The right lateral flexion angle of the head for c = –7.0 cm was significantly larger than that for c = 7.0 cm.

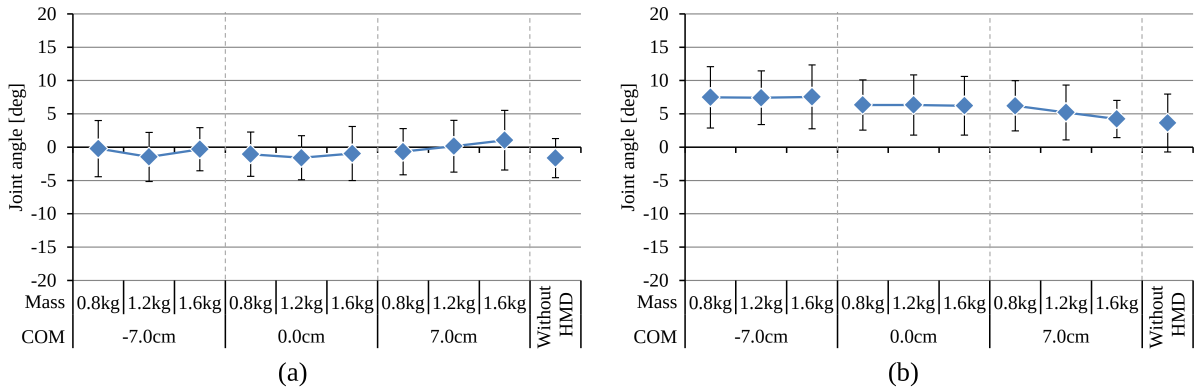


Fig. 7 Joint angles in the look-down posture: (a) anterior flexion angle of the trunk (b) right lateral flexion angle of the head

3.2 Joint torque ratios

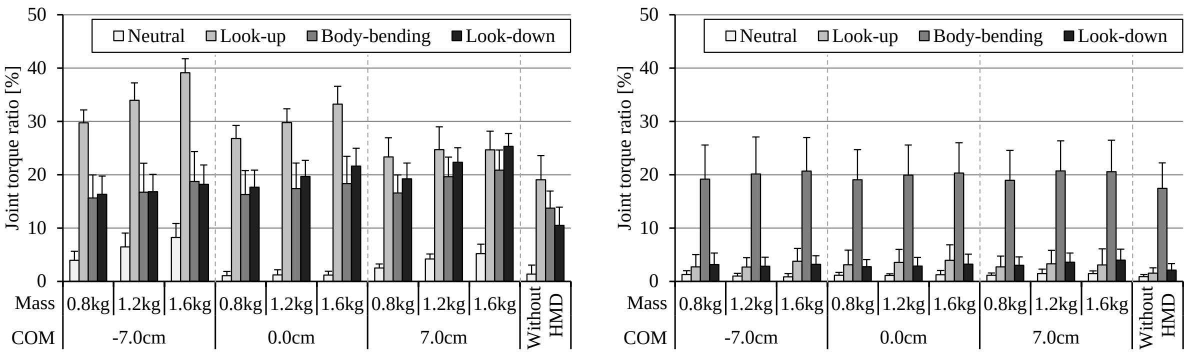
3.2.1 Neck

Figure 8 shows the average JTRs. For the neck JTR, the effects of mass and COM were significant for all test postures: [$F(2, 196) = 42.1$, $p < 0.01$] for the natural posture and the mass; [$F(2, 196) = 191$, $p < 0.01$] for the natural posture and the COM; [$F(2, 196) = 113$, $p < 0.01$] for the look-up posture and the mass; [$F(2, 196) = 349$, $p < 0.01$] for the look-up posture and the COM; [$F(2, 196) = 22.6$, $p < 0.01$] for the body-bending posture and the mass; [$F(2, 196) = 10.4$, $p < 0.01$] for the body-bending posture and the COM; [$F(2, 196) = 123$, $p < 0.01$] for the look-down posture and the mass; and [$F(2, 196) = 210$, $p < 0.01$] for the look-down posture and the COM. In addition, the interaction was significant for the neutral, look-up, and look-down postures: [$F(4, 196) = 11.3$, $p < 0.01$] for the neutral posture, [F(4,

196) = 19.7, $p < 0.01$] for the look-up posture; and [$F(4, 196) = 11.5$, $p < 0.01$] for the look-down posture. The neck JTR increased with an increase in mass for all test postures. In case of the natural posture, the neck JTR for c = –7.0 cm was highest, followed by c = 7.0 and 0.0 cm. For the look-up posture, the neck JTR decreased with an increase in COM. The neck JTR increased with an increase in COM for body-bending and look-down postures.

3.2.2 Lumbar

For the neutral posture, the effect of COM [$F(2, 196) = 5.66$, $p < 0.01$] and the interaction between mass and COM [$F(4, 196) = 3.72$, $p < 0.01$] were significant. The effect of mass was significant for the look-up [$F(2, 196) = 3.11$, $p < 0.05$] and body-bending postures [$F(2, 196) = 10.2$, $p < 0.01$]. For the look-down posture, the effects of mass [$F(2, 196) = 3.76$, $p < 0.05$] and COM [$F(2, 196) = 5.14$, $p < 0.01$] were significant. The lumbar JTR for m = 0.8 kg was lower than the other two mass values in the case of body-bending posture. The average JTR of lumbar was less than 4% for all test postures in HMD condition, except the body-bending posture.



(a) (b)

Fig. 8 Joint torque ratios: (a) neck (b) low back

3.3 Subjective scores

Figure 9 shows the average subjective difficulty. The effects of mass and COM were significant for all three test postures, of which the subjective evaluation was conducted: ([$F(2, 196) = 32.1$, $p < 0.01$] for the look-up posture and the mass; [$F(2, 196) = 19.7$, $p < 0.01$] for the look-up posture and the COM; [$F(2, 196) = 57.6$, $p < 0.01$] for the body-bending posture and the mass; [$F(2, 196) = 22.0$, $p < 0.01$] for the body-bending posture and the COM; [$F(2, 196) = 40.6$, $p < 0.01$] for the look-down posture and the mass; and [$F(2, 196) = 9.97$, $p < 0.01$] for the look-down posture and the COM). The COM c = 0.0 cm shows lower subjective difficulty than the other two COMs in the three test postures. In addition, the subjective difficulty decreased with a decrease in the mass.

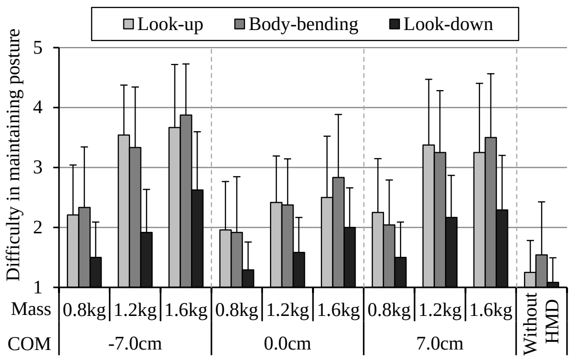


Fig. 9 Subjective difficulty in maintaining posture

4. Discussion

4.1 Joint angles

4.1.1 Neutral posture

The effect of COM was significant for the left rotation angle of the head. However, the difference of the angle from the ‘without HMD’ condition was only 4° at maximum. Therefore, the posture during gazing was almost constant, irrespective of the mass and COM of HMD. The effect of eye dominant may be one possible reason for that the left rotation angle showed negative value (or rotate to the right). Pradham et al. (2001) reported that the head rotates to the dominant eye side to make the non-dominant eye close to a visual target. Unfortunately, we did not check the eye dominant of our subjects. However, the number of right eye dominance was larger than that of left according to some report (the number of right eye dominance was 75 to 85%) (Pradham et al., 2001; Matherona et al., 2008; Gandelman-Marton et al., 2010). Under an assumption that the most of our subjects was right eye dominance, perhaps they slightly rotated their head rightward to make their left eyes close to the target when they gaze with the neutral posture whereas they faced the front when calibrating the internal measurement unit.

4.1.2 Look-up posture

The subjects extended and left rotated their neck joint to gaze at the target objects. As the COM moved backward, the subjects were able to further extend their neck joints. This was because the neck extension moment caused by the weight of HMD increased due to the increase of moment arm between the rotation center of neck joint and COM of HMD. In addition, the effect of COM was significant for the left rotation angle of the head. However, the difference of the left rotation angle from the without HMD condition was only 5° at maximum; thus, the left rotation angle of the head was hardly affected by the HMD conditions.

4.1.3 Body-bending posture

To gaze at the target object, the neck joint was extended, the right lateral flexed, and the left rotated; moreover, the trunk was anteriorly flexed and the right lateral was flexed. The subjects extended the neck joint to reduce the neck flexion moment imposed by the head and HMD because their trunks were anterior flexed. However, in the case of m = 1.6 kg, the anterior flexion angle of the head became large when c = 7.0 cm was compared with c = 0.0 cm. This implies that the subjects found it difficult to take a posture that reduced the physical workload in the neck when the COM was located in front of the HMD. However, the difference in the anterior flexion angles of the neck was approximately less than 3°; hence, the effect of COM might be ignored. The neck joint was laterally flexed to the right when the mass of HMD was relatively low, whereas it was laterally flexed to the left when the mass was relatively high. This was because the subjects pull up their head segments in order to inhibit the increase in neck joint torque accompanied by the increase in mass of HMD. In the body-bending posture, the trunk was anteriorly and laterally flexed to the right, and rightward rotation torque was generated at the neck joint when the COM was located in front of the HMD. Therefore, the left rotation angle of the neck for c = 7.0 cm was smaller than the other two COMs.

4.1.4 Look-down posture

The subjects anterior flexed their neck joint to gaze at the target objects. The effect of COM was significant for the right lateral flexion angle of the head and anterior flexion angle of trunk. However, the difference of these angles compared with the without HMD condition was only 4° at maximum. Therefore, the look-down posture was hardly affected by the HMD conditions.

4.2 Joint torque ratios

4.2.1 Neutral posture

The neck JTR for c = –7.0 and 7.0 cm was higher than that for c = 0.0 cm. This was because c = –7.0 and 7.0 cm increased the moment arm between the neck joint center and the COM of HMD, whereas the COM of HMD for c = 0.0 cm was located immediately above the neck joint center. The neck JTR for c = 0.0 cm was hardly affected by the mass of HMD because the moment arm was almost zero. However, the neck JTR for c = –7.0 and 7.0 cm increased with an increase in the mass of HMD because their moment arms were relatively long. The difference in lumbar JTRs for various HMD conditions was less than 1%; therefore, it was hardly affected by the HMD condition.

4.2.2 Look-up posture

The look-up posture brought the COM of c = 7.0 cm closer to the point immediately above the neck joint center; subsequently, the moment arm and neck JTR increased with decrease in the COM of HMD. The neck JTR for c = 7.0 cm was hardly affected by the mass of HMD because its moment arm was almost zero, whereas that for c = –7.0 and 0.0 cm increased with increase of the mass of HMD because their moment arms were longer. The difference in the lumbar JTRs for various HMD conditions was less than 1%; therefore, it was hardly affected by the HMD conditions.

4.2.3 Body-bending posture

The neck JTR showed an increasing trend with an increase in the COM. However, the difference in the neck JTRs for the COM was less than 2% for each mass condition. Therefore, the moment arm between the neck joint center and the COM of HMD was almost constant, irrespective of the COM condition. The lumbar JTR of the body-bending posture was relatively high than the other test postures because the body-bending posture required trunk flexion. Reducing the mass of HMD was effective in reducing the physical workload on lumbar in case of body-bending posture.

4.2.4 Look-down posture

The look-down posture brought the COM of c = –7.0 cm closer to the point immediately above the neck joint center, and the moment arm and neck JTR increased with increase in the COM of HMD. The neck JTR for c = –7.0 cm was hardly affected by the mass of HMD because the moment arm was almost zero, whereas that for c = 0.0 and 7.0 cm increased with an increase in the mass of HMD because their moment arms were longer. The difference in lumbar JTRs among the HMD conditions was less than 1%; therefore, the lumbar JTR was hardly affected by the HMD conditions.

4.3 Subjective score

The lower HMD mass reduced the subjective difficulty in all test postures for which the subjective evaluation was conducted because it reduced the physical workload at the neck and lumbar. For all three test postures, the subjective difficulty for c = –7.0 and 7.0 cm was higher than that for c = 0.0 cm. In the case of look-up posture, the backward COM increased the neck JTR; thus, the subjective difficulty increased in c = –7.0 cm. In the case of body-bending posture, the COMs of c = –7.0 and 7.0 cm generated left and right rotation torques, and then the subjective difficulty increased. In the case of look-down posture, the forward COM increased the neck JTR, and the subjective difficulty increased in c = 7.0 cm. In addition, some subjects answered that they perceived discomfort due to compression force from HMD at the nose and backside of the head when the COM was located forward and backward, respectively. Therefore, perceived discomfort due to wearing the HMD may also affect the increase of subjective difficulty in c = –7.0 and 7.0 cm.

4.4 Approximate functions of joint torque ratio for neck joint

Approximate functions of the neck JTR for each test posture were predicted to investigate the effects of recommended ranges of the mass and COM of HMD. The lumbar JTR showed very low values in all test postures, except the body-bending posture, irrespective of the HMD conditions. In addition, the relatively high lumbar JTR in the body-bending posture was mainly caused by trunk flexion. Therefore, the lumbar JTR was ignored in this study for the purpose of simplification. The approximate functions of neck JTR were predicted by quadratic polynomials with cross term. Their independent variables were the mass m and COM c of the HMD. The regression coefficients were determined based on the least-square method by using the average neck JTR as the training data. Table 1 describes the regression coefficients of approximate functions and their determination coefficients for each test posture. The determination coefficients were more than 0.9 in all test postures; thus, they were deemed to have enough accuracy.

Figure 10 shows the contour plots of the four test postures. The darker area indicates the lower neck JTR, and the interval of contour lines is set at 1% in JTR. The lower HMD mass resulted in a lower neck JTR for all test postures. In addition, the contour lines interval becomes sparser in the area of lower HMD mass. Therefore, the neck JTR hardly varied relatively, even though the COM of the HMD varied when the HMD mass was low. It implies that the lower HMD mass makes it easier for designers to adjust the COM position, considering the physical workload of the neck.

The COM, which minimized the neck JTR, changed depending on the test postures. The neck JTR reached minimum in approximately c = –2 to 4 cm, c = 0 to 2 cm, c =7 cm, and c = –5 to –3 cm for neutral, look-up, body-bending, and look-down postures, respectively. The size and position of contents displayed by HMD may vary depending on the intended use of the HMD. Therefore, the COM of the HMD should be designed by considering the intended use of the HMD to reduce the physical workload of the neck. For example, it is desirable to set the COM forward for the HMD used in the design reviews of buildings and industrial plants, because such a design review displays relatively large virtual objects and imposes the users to take the look-up posture. In the case of assembly tasks support, the COM of the HMD should be relatively backward because workers in assembly lines are expected to keep their eyes mainly downwards.

We assumed that the total neck workload (TNW) was expressed by the weighted sum of workload in all four test postures so that the function reflects the relative impact level of each test posture. The TNW W_{Total} was defined as follows:

$$W_{Total} = \alpha_N \cdot w_N + \alpha_U \cdot w_U + \alpha_B \cdot w_B + \alpha_D \cdot w_D \quad (1)$$

$$\alpha_N + \alpha_U + \alpha_B + \alpha_D = 1 \quad (2)$$

where w_N, w_U, w_B, and w_D are the approximate functions of the neutral, look-up, body-bending, and look-down postures, respectively. In addition, α_N, α_U, α_B, and α_D represent the weight coefficients of each test posture. As an example, the TNW function with equally set weight coefficients (i.e., $\alpha_N = \alpha_U = \alpha_B = \alpha_D = 0.25$) is shown in Fig. 11. It was expected that the TNW could be minimized by setting the COM of HMD slightly forward (c =0 to 4 cm) if the four postures are attained at the same rate. Note that the above-mentioned recommended range of the COM was based on equally set weight coefficients. Designers should determine the appropriate weight coefficients of TNW function, based on the intended use of HMD and then determine the optimal COM position.

Table 1. Regression and determination coefficients of approximate functions of neck joint torque ratio for each test posture

	Neutral posture	Look-up posture	Body-bending posture	Look-down posture
Center of mass *c* [cm]	$1.12{\times}10^{-4}$	$1.49{\times}10^{-3}$	$1.48{\times}10^{-4}$	$-7.46{\times}10^{-4}$
Mass *m* [kg]	$6.95{\times}10^{-2}$	$7.09{\times}10^{-2}$	$6.61{\times}10^{-2}$	$3.33{\times}10^{-2}$
c^2	$8.01{\times}10^{-4}$	$-1.38{\times}10^{-4}$	$1.39{\times}10^{-4}$	$1.47{\times}10^{-5}$
m^2	$-1.67{\times}10^{-2}$	$2.39{\times}10^{-4}$	$-1.12{\times}10^{-2}$	$6.75{\times}10^{-3}$
$c \times m$	$-1.43{\times}10^{-3}$	$-7.21{\times}10^{-3}$	$1.06{\times}10^{-3}$	$3.71{\times}10^{-3}$
constant	$-4.59{\times}10^{-2}$	$2.14{\times}10^{-1}$	$1.12{\times}10^{-1}$	$1.46{\times}10^{-1}$
Determination coefficient	0.925	0.996	0.933	0.999

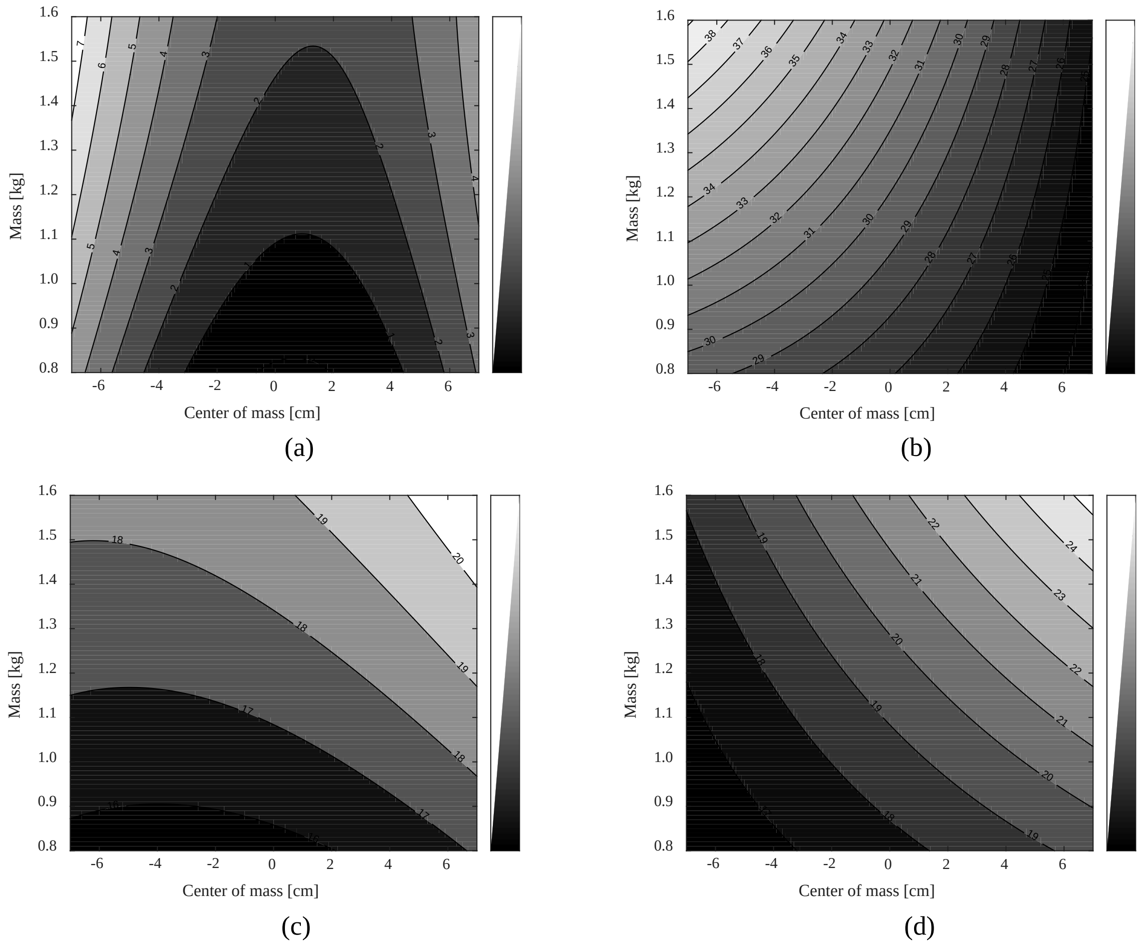


Fig. 10 Approximate functions of joint torque ratio in the neck for each test posture: (a) neutral posture (b) look-up posture (c) body-bending posture (d) look-down posture

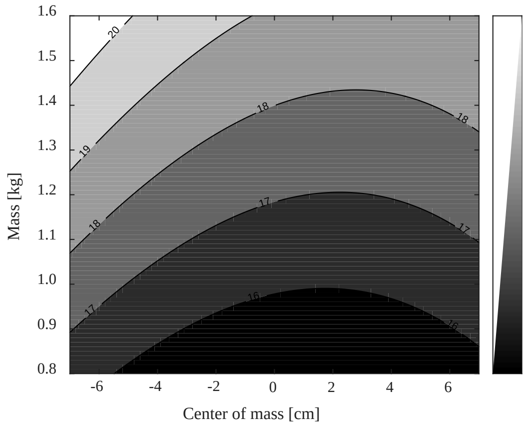


Fig. 11 Total neck workload function of four test postures with equal weight

4.5 Recommendation and Limitation

The look-up posture shows the highest neck JTR among the four test postures; therefore, HMD users should pay attention not to take too much look-up posture. The optimal COM position varied depending on the posture. If a designer cannot predict the head posture of HMD users, the optimal COM for the TNW function with equally set weight coefficients (c =0 to 4 cm) is a passable solution. The slightly forward COM reduces the JTR of the look-up posture that shows the highest JTR; thus, it is appropriate in order to minimize the maximum physical workload. Of course, it is desirable that the mass is as low as possible.

The prototype manufacturer (Canon Inc.) intended to develop a high-accuracy and high-definition HMD for industrial use rather than consumer use such as Oculus Rift (Oculus Inc.) and HTC Vive (HTC Inc.). The image quality and mass of HMD are in trade-off. Therefore, as a fundamental data, the physical workload with a wide mass range was required. However, the mass of HMD for consumer use is less than 0.5 kg that is out of the range of our experimental condition. The physical workload of lighter weight HMD should also be investigated to provide designers and consumers information of the existing products.

The JTRs with relatively short duration were evaluated in this study. However, in the actual use case, HMD users keep viewing displayed contents for a certain period of time. To evaluate the fatigue when using HMD, the effect of duration should be investigated. Moreover, the intended duration may determine the recommended upper limit of HMD mass because the magnitude of physical workload and maximum time that can hold a load are strongly related each other.

It should be noted that this experiment was conducted with a single HMD and healthy young adult subjects. It is possible that the working posture are affected by the view angle of HMD, age, and musculoskeletal disorder symptoms and the JTRs may change accordingly. Therefore, the influences of these characteristics should be investigated when optimizing the HMD parameters.

The subjective scores are not completely in line with the neck and trunk JTRs because the subjective evaluation probably does not depends on a single JTR. This mismatch may be due to the simultaneous evaluation of several physical factors such as JTRs, dynamic stability of head, visibility, contact pressure between HMD and head, and so on. However, it is difficult to cover the all possible physical factors that affect the subjective evaluation. In this study, the JTR was used as the most fundamental indicator for the physical workload; because a reduction in the JTR directly leads to a reduction in physical workload. However, it is necessary to clarify the effect of physical factors other than the JTR in order to further enhance the satisfaction of HMD users.

5. Conclusions

The body segment postures of the neck and lumbar region while gazing with an HMD at the target objects were evaluated for four test postures: the neutral, look-up, body-bending, and look-down postures. The physical workloads of the neck and lumbar were calculated and evaluated in order to investigate the effects of the mass and COM of the HMD on the workload. The major findings are as follows:

1. In the case of look-up posture, the subjects extended their neck joint when the COM position moved backward. In the case of body-bending posture, the subjects with relatively low HMD mass flexed their neck joint rightwards, whereas those with relatively large HMD mass flexed them leftwards. The body segment postures were hardly affected by the mass and COM of HMD in the case of neutral and look-down postures.
2. The lumbar JTR was relatively high in the body-bending posture; however, it showed very low values (less than 4%) in the other test postures. The neck JTR showed high values in all test postures, and varied depending on the HMD conditions. The high lumbar JTR in the body-bending posture was mainly caused by the body flexion. Therefore, the physical workload reduction in the neck is quite important to consider in an ergonomic HMD design.

3. The lower mass reduced the neck JTR. The optimal COM position for the neck JTR varied depending on the test posture. The recommended COM positions for each test posture were as follows: around the top of the head for the neutral posture, forward for the look-up posture, and backward for the body-bending and look-down postures.

HMD is just spreading and there is no clear guideline on the use. It is necessary to conduct experiments under various conditions with regard to physical workload. Researchers are required to gather knowledge on the use of HMD and establish guidelines for comfortable use of HMD.

Acknowledgements

We received a generous support from Canon, Inc. with respect to the use of the HMD prototype and instructions on the setting of experimental conditions.

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