Molecular & Cellular Biomechanics

Tech Science Press

Quantitative Method for Biomechanical Evaluation of Bedding Comfortableness

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Abstract: Comfortable bedding is usually designed subjectively because of the difficulty in performing a quantitative evaluation. This paper proposes a quantitative evaluation method of comfortableness of beddings. The bedding shape determining how comfortable an individual may feel in using it depends on the body shape and normal posture of individuals. The internal physical load is expected to relate to the comfortableness of bedding. However, only a few quantitative discussions exist on the relation between the comfortableness of bedding and physical load. This study proposes a new evaluation method of physical load in a relaxed posture. The strain energy of muscles and joints was used as an indicator of physical load. To estimate physical load, a neutral body position was simulated from a natural standing posture and was used as a reference posture with the neutral condition of muscle lengths. By considering individual differences, multiple models of neutral body position were provided. We simulated individual differences of a comfortable pillow height using the proposed models. Physical load in a relaxed posture was varied according to the models. Calculated results show that physical load becomes small when a pillow is comfortable. For both subjective pillow comfortableness and smallness of physical load, there is a similar tendency that the low pillow with the small height difference between head and neck is preferable if the concave depth of back shape of head and neck is small. Moreover, the results show that muscles and joints equally affect the comfortableness of designed pillow. This implies that less total energy required for maintaining the posture contributes to pillow comfortableness.

Keywords: Pillow design; comfort; physical load; musculoskeletal model; neutral body position; biomechanical evaluation

1 Introduction

Sleep is important for good health and quality of life. Requirements for a comfortable sleep environment had been discussed from various points such as lighting [1,2], thermal conditions [3-5], acoustics [6,7] and vibrations [8,9]. Beddings can affect the comfortableness of sleep. Further, there is an active discussion on beddings including pillow from an ergonomic perspective based on the use of subjective evaluation of material [10] and its physical properties such as hardness, touch, and shape [11-14]. However, few studies looked into the individual differences in preference of pillow, although the comfortableness of pillow is expected to relate to physical load.

Previously [15], we proposed a comfortable pillow design method for individuals, named the comfortable pillow formulas (CPFs). The CPFs is based on the significant correlations between comfortable pillow height of neck and head areas at the time of use and body shape of the back head and neck in natural standing. The subjective evaluation showed that CPF can be used to design comfortable pillows. However, the validity of the CPFs needs to be objectively evaluated. Thus, this requires determining the quantitative index of comfort in a relaxed posture. Electromyogram (EMG) is an

DOI: 10.32604/mcb.2019.08123

objective indicator commonly used to evaluate muscle fatigue; however, EMG is not practical for status assessment of relaxing muscles [16]. Other studies used measured body pressure distribution on the mattress when an individual using it feels comfortable [17]; however, the proper body support is different among individuals owing to different body shape and weights. Finite element analysis has been used as a numerical method to estimate the bedding shape at the time of use [18]; however, it is difficult to precisely simulate physical load in contact with soft beddings.

This study proposes a new evaluation method of pillow comfortableness based on musculoskeletal simulation of physical load in relaxing posture. Section 2 presents a biomechanical simulation method of physical load in a relaxed posture. The method uses strain energies of muscles and joints as indicators of stress condition of a relaxed posture. Section 3 presents the simulation results of comfortable pillow height for individuals. Finally, discussions and conclusions are presented in Sections 4 and 5, respectively.

2 Physical Load in a Relaxed Posture

Fig. 2 shows an overview of the proposed method for a biomechanical simulation of physical load in a relaxed posture of individuals. Physical load in a relaxed posture can be attributed to strain energy of muscles and joints. To simulate the strain energy, a reference posture in which muscle length becomes natural was estimated. We assumed that a neutral body position (NBP), which is a relaxed posture under zero gravity [19], can be regarded as a reference posture in which muscles and joints are in the neutral condition. This NBP differs among individuals [19]. Therefore, NBP was estimated for each individual to minimize muscle strain energy in an NSP of individuals. Relaxed posture and its support condition can be simulated using a musculoskeletal model with varying parameters determining posture. Herein, this study uses two types of pillow height at the time of use as the parameters. Physical load in a relaxed posture can be described using the strain energy of muscles and joints. In a given relaxed posture, the calculated physical load can vary with NBP. This means that the proposed method considers the individual difference in the case of using the same pillow. In this paper, AnyBody Modeling System$^{\text{TM}}$ was used not just for muscle force as done in previous studies but for simulating muscle length and joint reaction force. Details are described below.

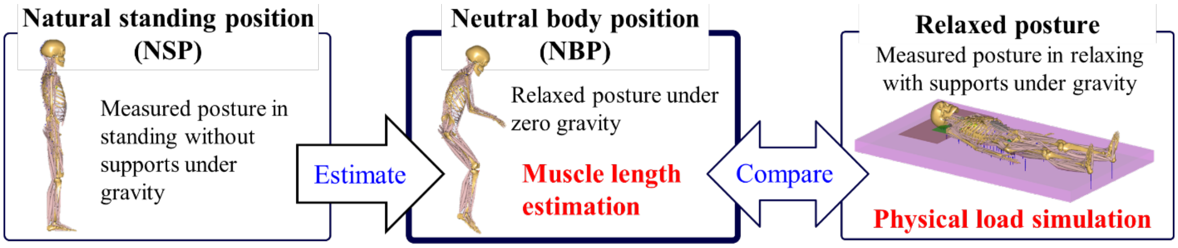


Figure 1: Overview of the proposed method

2.1 Evaluation Formula of Physical Load

Musculoskeletal simulation of the human body is a famous approach for estimating physical load. The simulation can be applied in many cases because exercise activity is usually accompanied by high muscle activity. Conversely, in a relaxed posture, muscles are hardly ever activated greatly. For instance, in a sleep posture, the human body is supported by bedding; therefore, muscles are almost not used. In addition, a negligible external force is enough to extend an unstimulated muscle at lengths less than 1.2 times its rest length [20-22]. Thus, muscles will be passively stretched and rarely output force as simulated in the mathematical muscle model. Due to this, the joint reaction force can also be small; however, joint strain should be taken into consideration because joints are sensitive to strain [23,24]. Therefore, the proposed method first defines the indicator of physical load in a relaxed posture U. The U can be calculated as follows:

$$U = w_m U_m + w_m U_j, \qquad (1)$$

where U_m denote the strain energies of muscles, U_j denote the strain energies of joints, w_m and w_j denote weight parameters of muscles and joints, respectively. A detailed information on w_m and w_j are presented in the discussion. The U_m can be calculated as follows:

$$U_m = V_m \frac{\sum_{i=1}^{N} u_{m_i}}{N} \tag{2}$$

where subscript i indicates muscle index, u_{m_i} denotes a strain energy per unit volume caused by passive stretch, N denotes the number of muscles in the body region of interest (BROI), V_m denotes the total volume of the muscles in the BROI. By assuming the muscle to be an isotropic elastic cylinder made of incompressible material (Poisson's ratio τ_m = 0.5) for simplification, the u_{m_i}can be calculated as follows:

$$u_{m_i} = \frac{1}{2} E_m \left(l_i / l_{i_{NBP}} - 1 \right)^2, \tag{3}$$

where E_m denotes the Young's modulus of muscle at rest ($E_m = 48.6$ kPa [25]). The l_i and the $l_{i_{NBP}}$ denote the lengths of the i^{th} muscle in a RP and in the NBP, respectively. The estimation method of $l_{i_{NBP}}$ is presented in Section 2.2. In this study, the BROI was set to cover all muscles, which have at least one attachment point in the skull or cervical vertebrae and therefore $V_m = 6.98 \times 10^{-4}$ m^3 [26].

Strains of joints are detected by ruffini mechanoreceptors in joints [24]. Therefore, strains of joints can also affect the subjective feeling of physical load. The strain energy of joints U_j can be calculated as follows:

$$U_j = \sum_k \{ V_{d_k} (u_{a_k} + u_{s_k}) \}, \tag{4}$$

$$u_{a_k} = \frac{{f_{a_k}}^2}{2 E_{j_k} {A_{j_k}}^2}, \tag{5}$$

$$u_{s_k} = \frac{{f_{s_k}}^2}{2 G_{j_k} {A_{j_k}}^2}, \tag{6}$$

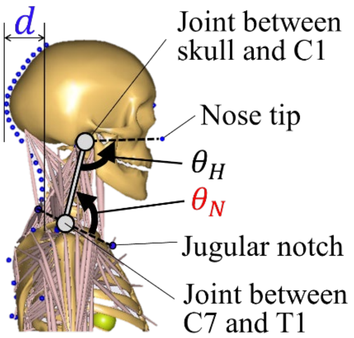
where subscript k denotes joint index, V_{d_k} denotes the volume of cartilage or intervertebral disc, u_{a_k} and u_{s_k} denote axial and shear strain per volume unit, f_{a_k} and f_{s_k} denote axial and shear force in the joint, E_{j_k} and G_{j_k} denote Young's modulus and shear modulus of the joint (cartilage or intervertebral discs), and A_{j_k} denotes transverse area of the joint, respectively. Mechanical properties of the joints are shown in Tab. 1. We assumed that all intervertebral discs are made of incompressible material ($\tau_j = 0.5$) and have the same size and property.

Table1: Property settings for joints in the BROI

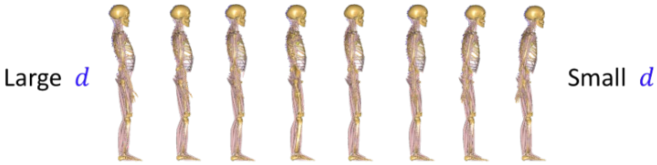
Parameter name	Symbol	Value	Note
Young's modulus	E_{j_k}	2.4 MPa	Reported value in [27,28]
Shear modulus	G_{j_k}	0.8 MPa	Calculated from E_{j_k} and τ_j.
Cross-sectional area	A_{j_k}	2.7×10^{-4} m^2	Average of reported value in [29]
Volume	V_{j_k}	1.5×10^{-6} m^3	Average of reported value in [29]

2.2 Estimation of Neutral Body Positions

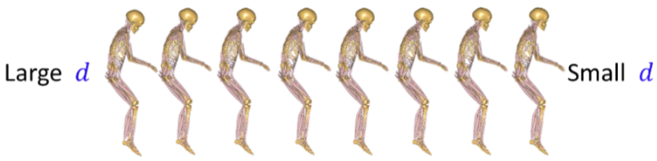
An NBP is a relaxed posture in zero gravity as reported by NASA in [19]. Because NBP is difficult to measure, it can be estimated from the NSP, one of the most stable standing postures with a small physical load. Our previous work [15] showed that NSP varies among individuals and correlations exist between the concave depth of back shape of the neck d (shown in Fig. 2(a)) and the joint angles of head and neck. Therefore, it is necessary to consider individual differences in NSP. We set multiple NSP models, and corresponding NBP models were estimated for each NSP. This procedure will be helpful to simulate individual difference of physical load in the same RP. The difference of NSP among individuals was considered together with parameterizing joint angles of head and neck, θ_H and θ_N, as shown in Fig. 2(a). Using an NSP model, $l_{i_{NSP}}$ for each muscle in BROI was simulated. According to $l_{i_{NSP}}$, an NBP can be estimated adaptively to minimize U_m in the corresponding NSP.



(a) parameter definition



(b) NSP models with varying d

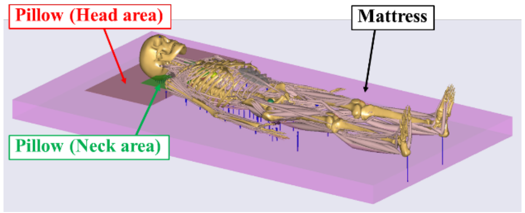


(c) estimated NBPs corresponding to NSPs

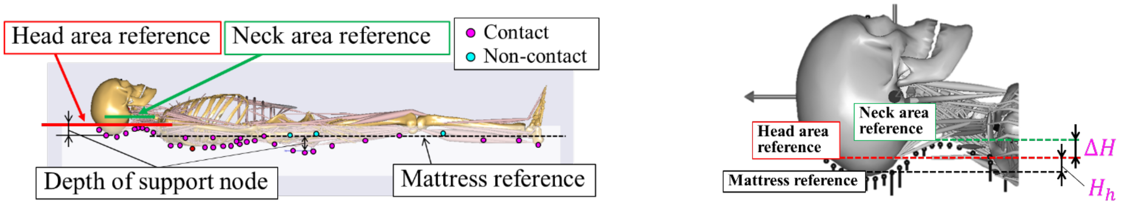
Figure 2: NBP estimation

2.3 Estimation of Physical Load in Relaxed Posture

Herein, we discuss the relative heights of pillow heights of the neck and head area to mattress effect on the joint angle, distribution of body support force, and physical load. Therefore, in the simulation conducted, three horizontal reference planes for support force calculation were set for head, neck, and the other body parts as shown in Fig. 3. The body support force was calculated based on the subduction of body surface nodes to each corresponding reference plane. Various pillow heights were simulated by changing heights of reference planes of each head and neck. The height difference of these two reference planes, ΔH, can be defined as $\Delta H = H_h - H_n$, where H_h and H_n denote the reference plane heights of head and neck to the mattress plane, respectively. In the series of simulations conducted, 1281 types of pillow height parameter pairs were set as shown in Tab. 2. The parameter ranges assume practical pillow shape. For each NBP and each pair of pillow heights, a relaxed posture can be estimated adaptively to minimize U_m.



(a) overview



(b) reference planes (c) pillow parameter definition

Figure 3: Sleep-environment model

Table 2: Pillow parameter settings in the simulation

H_h	Range: $0 \leq H_h \leq 120$, Interval: 2 mm, 61 conditions
ΔH	Range: $-40 \leq \Delta H \leq 0$, Interval: 2 mm, 21 conditions
H_n	$H_n = H_h - \Delta H$

After the series of simulation of RP, the top 10 pairs of $(H_n, \Delta H)$ that minimize U for each NSP were chosen to calculate the pair of weighted average pillow height parameters $\left(\acute{H}_n, \acute{\Delta H}\right)$ as follows:

$$\acute{H}_n = \sum_{c=1}^{10} \left(\frac{11 - c}{\sum_{c=1}^{10} c} H_{n_c} \right), \tag{7}$$

$$\acute{\Delta H} = \sum_{c=1}^{10} \left(\frac{11 - c}{\sum_{c=1}^{10} c} \Delta H_c \right), \tag{8}$$

where H_{n_c} and ΔH_c denote the values of H_n and ΔH of the c^{th} smallest U_{RP}, respectively.

3 Results

The following results are obtained in the case of $(w_m, w_j) = (1.0, 1.0)$. The validity of this weight parameter is discussed in the subsequent section.

3.1 Strain Energy of Muscles and Joints

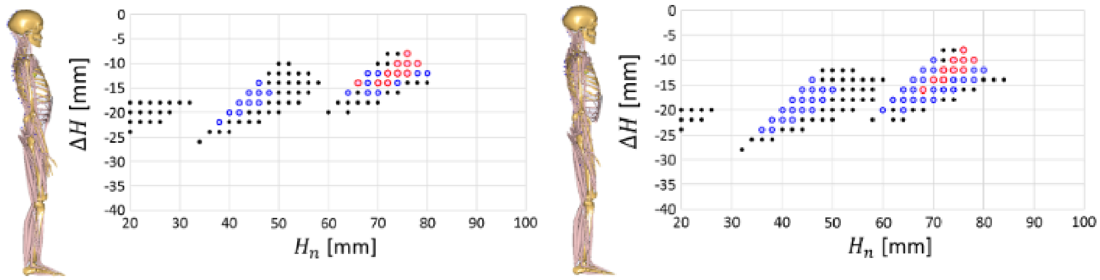
Tab. 3 shows the simulation result of strain energy values in the case of minimum U. Both U_m and U_j have the same order of magnitude when U_{RLP} is minimized. In the series of simulations conducted, the estimated maximum muscle activity was less than 0.9%. This value is much smaller than in the value obtained when performing an exercise; hence, the estimated muscle force can be negligible.

Table 3: Simulation result of strain energy values in the case of minimum U

									unit: × 10^{-4}[J]
	(Small d)			NSP model				(Large d)	**Avg.**
	1	2	3	4	5	6	7	8	
U	7.78	9.02	7.18	7.09	6.95	6.41	5.89	5.74	7.01
U_m	4.36	5.60	3.76	3.67	3.52	3.17	2.83	3.85	3.85
U_j	3.42	3.42	3.42	3.42	3.42	3.24	3.06	1.88	3.16

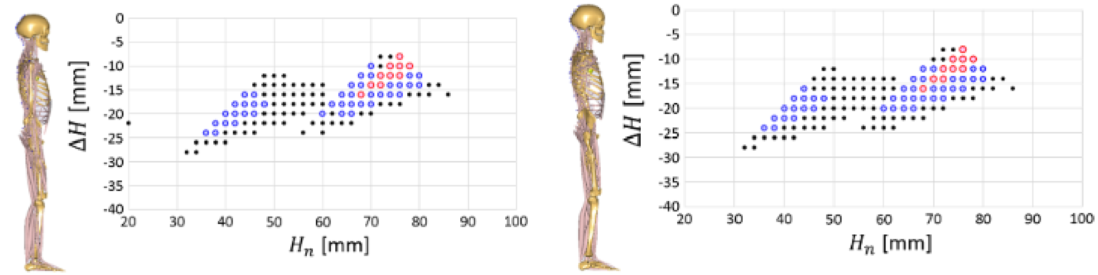
3.2 Pillow Parameters of Small U

Fig. 4 shows the distribution of pillow parameters of small U for each NSP model. For an NSP model with small d, which represents when an individual stands with round back, the U becomes small when the person is lying with a pillow having high H_n and large ΔH. In contrast, for an NSP model with large d, which represents when an individual stands with straight back, the U becomes small when the person is lying with a pillow having low H_n and small ΔH.



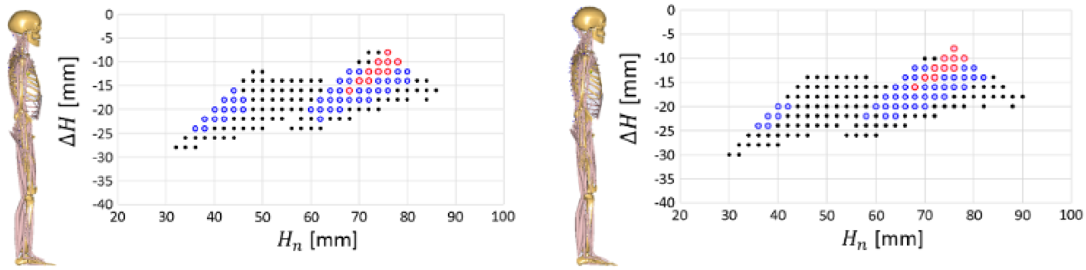
(a) model 1 (small d)

(b) model 2



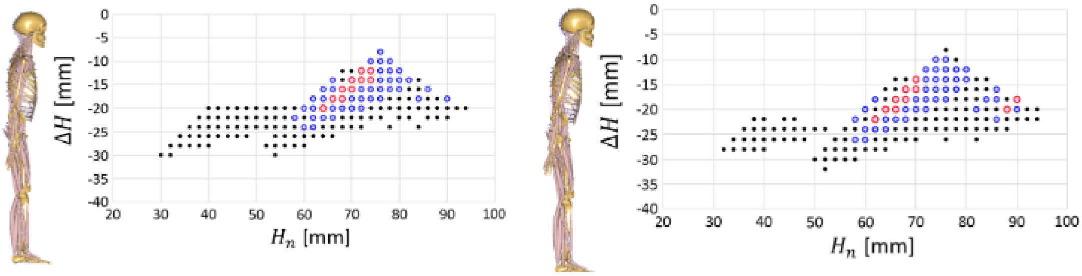
(c) model 3

(d) model 4



(e) model 5

(f) model 6



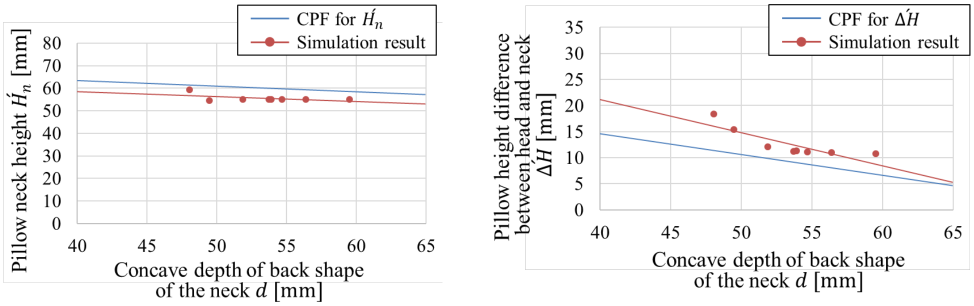
(g) model 7

(h) model 8 (large d)

Figure 4: Distribution of pillow parameters of small U for each NSP model

3.3 Pair of Weighted Average Pillow Height Parameters

Fig. 5 shows the relation between d and the set of $(\acute{H}_n, \Delta\acute{H})$ and the CPFs. The results show a similar tendency to the CPFs that $\acute{H}_n$ and $\Delta\acute{H}$ become small as d gets large.



(a) d and $\acute{H}_n$ (b) d and $\Delta\acute{H}$

Figure 5: Relation between d and the set of $(\acute{H}_n, \Delta\acute{H})$ and the CPFs

4 Discussion

The orders of U_m and U_j are the same as shown in Tab. 3. From V_m, E_m and the average U_m, the average strain of the muscles $\acute{\varepsilon}$ can be led as $\acute{\varepsilon} = \sqrt{2\,U_m/(V_m E_m)} \cong 1.1 \times 10^{-2}$. This means that muscles in BROI were stretched only 1% from their original length when using a comfort pillow. The average U_j indicates that the average shear force $\acute{f}_{sk}$ for each neck joint is almost 3 N when body weight is 60 kg and weight of the neck area is about 2 kg [30,31]. The values of $\acute{\varepsilon}$ and $\acute{f}_{sk}$ indicate that the proposed method successfully generated an RP with a less physical load on head and neck.

As shown in Fig. 5, the pillow height parameters and CPFs did not completely match, and the sets of $(\acute{H}_n, \Delta\acute{H})$ did not follow a straight line relation. This is due to the parameter setting of reaction force calculation in the simulation. However, the results obtained show a similar tendency to the ones obtained using CPFs: That $\acute{H}_n$ and $\Delta\acute{H}$ become small when d gets large. This suggests that the CPFs proposed in our previous study can be used to produce the posture in which the mechanical load of the head and neck is small.

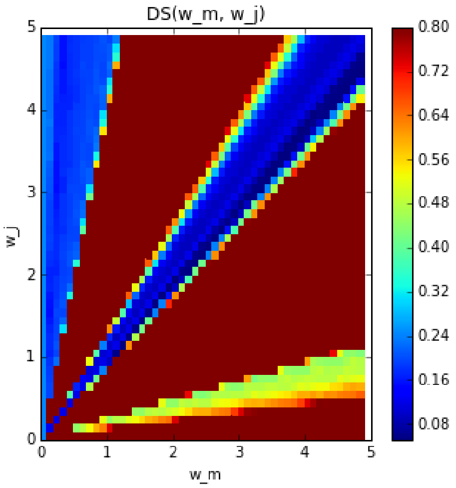


Figure 6: The $DS(w_m, w_j)$ values along with weight parameter set (w_m, w_j)

An important question that may be raised is was the weight parameter setting appropriate? We tried to evaluate the weight parameter setting by comparing various pairs of the weight parameters (w_m, w_j), prepared by changing their values from 0.1 to 5.0 in steps of 0.1, respectively. For each pair of (w_m, w_j), the same procedure described in Section 2 were applied, and then, the difference of regression formulas of $\acute{H}_n$ and $\Delta\acute{H}$ to the d from the CPFs can be calculated as $DS(w_m, w_j)$ using the following equation:

$$DS(w_m, w_j) = \left(k_{n_{CPF}} - k_n\right)^2 + \left(k_{\Delta_{CPF}} - k_\Delta\right)^2, \tag{9}$$

where k_n and k_Δ are coefficients of the linear regression formulas to d of the two pillow parameters H_n and ΔH, respectively. Fig. 6 shows that the $DS(w_m, w_j)$ is minimized when $w_m \cong w_j$. This implies that muscles and joints can affect the comfort of using pillow accordingly; hence, the $(w_m, w_j) = (1.0, 1.0)$ is appropriate for the proposed method.

5 Conclusion

In this paper, we proposed a new evaluation method of comfortableness in a relaxed posture (RP) based on the estimation of physical load in the posture. The physical load was represented by the sum of strain energies of muscle and joint. To estimate physical load, we adopted a neutral body position (NBP) as a reference posture with the neutral condition of muscles length. Because NBP is difficult to measure, it was estimated from a natural standing posture (NSP). Multiple NSP models and the corresponding NBP models were estimated by considering individual differences in NSP. We estimated muscle strain energy in a posture by using musculoskeletal simulation with the assumption that the muscle lengths in NBP are the natural ones. We also estimated the strain energy of the joint. Further, physical load in RP was estimated with varying pillow heights of each neck and head areas as well as considering individual NSP difference. The results obtained show that physical loads in muscles and joints were comparably small as U became small. Further, we demonstrated how muscles and joints affect the comfortableness of designed pillow. This implies less total energy for maintaining the posture contributes to pillow comfort. Finally, we showed that the CPFs proposed in our previous study can be used to design a pillow that can produce a sleep posture with less physical load for individuals.

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