Effect of Backboard Use During Chest Compressions on Total Compression Depth According to Mattress Firmness: A Computational Simulation Study

A short running title of less than 50 characters; Backboard Effects in Computational CPR Simulation

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Abstract (200 words)

Purpose: Chest compressions during in-hospital cardiac arrest are often performed on mattresses of varying firmness, where mattress displacement may reduce effective thoracic deformation. This study evaluated the mechanical effects of backboard use, as well as backboard thickness and size, on total compression depth (TCD) under simulated conditions. Methods: A three-dimensional thorax model was constructed from human chest CT images using finite element analysis. Chest compressions were simulated under a constant compression force of 250 N. TCD, defined as the sum of thoracic deformation and mattress displacement, was measured to assess the effects of mattress firmness, backboard presence, and backboard dimensions. Results: Backboard use reduced TCD compared with no backboard, with a greater effect on softer mattresses. Increasing backboard thickness beyond 7 mm produced minimal additional reduction in TCD. Larger backboard dimensions were associated with small decreases in TCD, indicating a ceiling effect. A backboard surface area exceeding approximately 3500 cm^2 provided limited additional mechanical benefit. Conclusion: Under constant-force simulation conditions, backboard use reduced mattress displacement and TCD, particularly on soft mattresses. Further increases in backboard thickness or size yielded minimal additional benefit. These findings provide mechanical insight into backboard characteristics relevant to optimizing chest compression conditions.

Keywords

backboard, chest compression, total compression depth, simulation

Introduction

According to the American Heart Association's Get With The Guidelines–Resuscitation (GWTG-R) registry, around 350,000 adult patients with in-hospital cardiac arrest (IHCA) underwent cardiopulmonary resuscitation (CPR) in the United States between 2000 and 2021, of whom 15.1% had a favorable neurological outcome.[1]

Previous research also suggests that adult patients undergoing CPR have improved neurological outcomes at a chest compression (CC) depth of ≥5 cm.[2] While patients with IHCA typically undergo CPR while lying on a mattress, the compression force applied by the rescuer is dissipated through both the required CC force and compression of the mattress (i.e., mattress displacement) under the patient, which may in turn reduce the CC depth. Previous studies have demonstrated that when performing CCs on mattresses with different firmness, CC depth differs depending on the type of mattress.[3,4] In particular, the use of a CC feedback device with a single force and deflection sensor may result in overestimation of CC depth if the patient is lying on a soft mattress, suggesting that actual CC may be shallower than expected both in manikin studies and in actual patients.[5,6]

Placing a backboard under the back of a cardiac arrest patient has conventionally been considered effective in maintaining optimal CC depth by reducing mattress displacement. Meta-analysis of studies on CPR performed on a manikin placed on a mattress or bed has shown that the use of a backboard improves CC depth but that the difference is marginal. The International Liaison Committee on

Cardiopulmonary Resuscitation was therefore unable to make a recommendation for the use of a backboard in the international consensus which formed the basis of its international CPR guidelines.[7] Moreover, the effects of a backboard may be dependent on the firmness of the mattress and the size of the backboard. A previous study in which CCs were performed on a manikin on three different bed surfaces showed that a backboard was effective only when used on the soft mattress.[8] Meanwhile, another study demonstrated that when CCs were performed on a manikin placed on two backboards of different sizes, the backboard size did not significantly affect mattress displacement.[9]

There are three issues with these previous studies. The first is that they compare CC depth using manikins rather than actual human patients so their findings may have been influenced by the mechanical properties of the manikins. The second issue is that the applied compression force differs according to the individual performing CCs and is not constant, suggesting that CC depth may become shallower over time as fatigue sets in. Furthermore, if the amount of mattress displacement during CCs differs according to the mattress firmness, the compression force applied may also be affected. The third issue is that these previous manikin studies have been limited to several backboard sizes and mattress types, and the different combinations used in each study have made it impossible to identify optimal values.

In the present study, 3D analysis of human CT scans was performed and a thorax model was created using finite element analysis (FEA). CCs were then simulated at a constant compression force that would be infeasible for an actual rescuer/participant, and the results were analyzed to determine how total compression depth (TCD)—calculated by adding CC depth and mattress displacement—was affected by mattress firmness, presence or absence of a backboard, and backboard thickness and size.

Materials and methods

Model creation

CT images (0.67-mm slice thickness) of the thoracic vertebrae, costae, costal cartilages, sternum, of an adult male (Japanese, aged 32 years) were obtained with the Brilliance 64 CT scanner (Philips Healthcare, Amsterdam, The Netherlands). The use of these CT images was approved by the ethics committee at the Center for Clinical Research, Yamaguchi University Hospital (Ube, Japan; approval no. H29-052).

Thorax model construction

Chest CT images (DICOM format) were uploaded to 3D image processing and model generation software (Simpleware ScanIP, Synopsys, Sunnyvale, CA) and the thoracic bone images were extracted and segmented. The segmented images were then exported as geometrical data (STL format) and uploaded into 3D CAD software (Autodesk Inventor Professional, Autodesk, San Francisco, CA). Discrete cross sections of the ribs, sternum, costal cartilages, vertebrae, and costovertebral joints were extracted and then joined to form the parts of the thorax model, which was then imported into simulation software (ANSYS Workbench, ANSYS, Canonsburg, PA) (Fig. 1a, 1b).

A half-symmetrical model was constructed to inhibit lateral deformation. This model simulates the ribs, sternum, costal cartilages, and spine. The rear surface of the model features a plate simulating the skin, a backboard, and a mattress (Fig. 1c). This model was constructed based on the assumption that the bones of the thorax are chiefly responsible for determining chest compliance during CCs. In the thorax model's default state, the ninth rib is in contact with the skin plate, and the points of contact between the thorax and the mattress are as indicated by the circles in Fig. 1a, 1b based on the actual positioning of back muscles and skin observed in the CT images.

A load displacement diagram for the analysis is presented in Fig. 2. The diagram shows nonlinearities similar to those reported in a previous cadaver study investigating the relationship between sternal loading and CC depth.[10] This suggests that the analysis model of the present study is capable of simulating CCs performed on an actual human patient.

Constraints of the model

The skin plate, backboard, and mat were attached at their respective contact surfaces to prevent displacement during loading. On the symmetry planes of the model and the bottom surface of the mat, each movement was restricted in the direction perpendicular to the surface. The two corners of the bottom surface of the mat were also fully fixed as shown by the circles in the image on the Fig. 1d.

Material attributes

Young’s modulus, Poisson’s ratio, bulk modulus, and shearing modulus of the simulation are shown in Table 1. The mattress thickness was 14 cm and the physical properties of the backboard were simulated based on the physical properties of the plastic material commonly used for backboards (Young’s modulus: 8.0×10^3 MPa; Poisson’s ratio: 0.35).

Young’s modulus of the mattress

Prior to the analysis, the firmness of various mattresses currently in use at our hospital were measured. Firmness was determined by placing a disk-shaped weight on each mattress and calculating Young’s modulus based on the amount of displacement. Young's modulus is defined as the amount of force per unit area required to compress a material to infinitesimal thickness. A higher modulus indicates greater resistance to deformation. Table 2 shows the calculated results for each of the four mattress types. Young’s modulus was lowest for an air mattress (Hillrom) at 10 kPa and highest for the Muranaka NST-2 mattress at 13 kPa. Young’s modulus of each mattress was used in the analysis.

Variables measured

The thorax model loading at a CC depth of 5 cm was calculated to be 250 N. A simulated load of 250 N was then applied with the backboard and thorax model placed on the mattress. Based on the results of this simulation, the effects of mattress firmness, presence or absence of the backboard, and backboard thickness and size on TCD were investigated.

Results

Presence or absence of the backboard

Based on a backboard thickness of 10 mm, a simulation was performed to determine how the presence or absence of a backboard changed the relationship between TCD and Young’s modulus of the mattress (Fig. 3a). The results showed that TCD tended to increase as the mattress firmness decreased. TCD tended to be lower when a backboard was used than when it was not used, regardless of mattress firmness. This trend became more pronounced as mattress firmness decreased.

Backboard thickness and size

1. Backboard thickness

The effect of backboard thickness on TCD was investigated. The backboard width was set at 50 cm and the length at 70 cm; the thickness was varied between 5 and 20 mm. The analysis results are shown in Fig. 3b. At a backboard thickness of ≥7 mm, thickness had almost no effect on TCD.

2. Backboard length

Backboard thickness was set at 10 mm, width was set at 50 cm, and length was varied between 40–80 cm (Fig. 3c). The results showed that TCD tended to decrease as backboard length increased, regardless of Young’s modulus of the mattress. However, at the range of firmness seen in mattresses used in the clinical setting (Young’s modulus: 10–13 kPa), TCD only differed by around 6–7 mm regardless of the backboard length.

3. Backboard width

Backboard thickness was set at 10 mm, length was set at 60 cm, and width was varied between 40–60cm (Fig. 3d). As a result, TCD tended to decrease as backboard width increased, regardless of Young's modulus of the mattress. However, at the range of firmness seen in mattresses used in the clinical setting (Young's modulus: 10–13 kPa), TCD differed by only around 2.5–3.5 mm regardless of the backboard width.

4. Backboard surface area

The relationship between TCD and backboard length and width when using mattresses with different levels of firmness is shown in Fig. 4a (mattress with Young's modulus of 10 kPa) and in Fig. 4b (mattress with Young's modulus of 13 kPa). The backboard thickness was set at 10 mm. The analysis results showed a ceiling effect at a backboard surface area of >3500 cm^2 (length 70 cm × width 50 cm), with any further increases in surface area yielding only a limited effect.

Discussion

In the present study, a computational model of the thorax was constructed, and CCs were simulated at a compression force of 250 N and CC depth of 5 cm. TCD includes both thoracic deformation and mattress displacement. Excessive mattress displacement may lead to overestimation of effective CC depth when feedback devices are used, potentially resulting in insufficient actual thoracic compression.[11] Therefore, reduction in TCD, particularly through minimization of mattress displacement, may contribute to more effective CCs by ensuring that applied force is preferentially translated into thoracic deformation rather than bed compression. The simulation analysis showed that TCD decreased when a backboard was used compared with when a backboard was not used. Moreover, this inhibitory effect on TCD became more pronounced as mattress firmness decreased. On the other hand, TCD was not affected at a backboard thickness of ≥7 mm. Although TCD tended to decrease with increasing backboard width and length, the difference in TCD was ≤7 mm. This was considered clinically insignificant when compared to the target depth for adult CCs recommended in guidelines (at least 5 cm, ≤6 cm).[12] A ceiling effect was observed when the backboard surface area exceeded 3500 cm², and further increases in surface area had only a limited effect on TCD. Therefore, the clinical significance of using excessively large backboards is considered limited.

In clinical practice, CCs are commonly performed with the intention of achieving a target CC depth rather than applying a constant force. In contrast, the present study employed a constant-force simulation model to isolate the mechanical effects of mattress firmness and backboard characteristics. This approach allows evaluation of how much of the applied force is dissipated by mattress deformation under standardized conditions. Accordingly, our findings should be interpreted as representing the mechanical environment underlying CCs when rescuers attempt to achieve adequate CC depth, particularly in situations where mattress deflection may reduce effective thoracic deformation.

The CC force of 250 N was selected to approximate the force required to achieve a CC depth of 5 cm in an average adult thorax. While CC force and depth may interact dynamically in clinical practice, the present approach allows isolation of mechanical effects attributable to mattress firmness and backboard characteristics under standardized loading conditions. In previous manikin studies, the manikin featured a spring assembly, so the compression force was directly proportional to the CC depth. However, a previous cadaver study showed that the relationship between sternal loading and CC depth is nonlinear.[10] It is therefore unclear whether the results of previous manikin studies are applicable to actual patients.

In the present study, 3D analysis was performed on human chest CT images, and the findings were used to construct a computational model of the thorax using FEA. The structural-mechanical properties of this model exhibited nonlinear load-displacement behavior similar to that reported in the previous cadaver study.[10] The precision of the study results was limited due to the fact that it used a computational simulation rather than actual human patients. However, we were able to investigate the effects of mattresses and backboards with greater precision than that permitted by manikin studies.

Furthermore, despite the fact that mattress firmness and backboard size are continuous variables, many previous studies have limited their comparisons to two or three types of mattresses and backboards. Even when using real-time feedback, the compression force applied is not constant and may be influenced by fatigue. In the simulations of the present study, the effects of mattress firmness and backboard size as continuous variables could be accurately estimated provided that the physical properties of the mattress and backboard are known.

1. Presence or absence of the backboard

Placing a backboard under the back of a cardiac arrest patient has conventionally been considered to be effective in maintaining optimal CC depth by reducing mattress deflection. However, a consensus has yet to be reached on the effects of a backboard placed on a mattress.

In a randomized, double-blinded, cross-over trial in which 23 hospital orderlies performed CCs on a manikin placed in a standard hospital bed, CC depth increased from 43 mm to 48 mm when using a backboard.[13] On the other hand, in a prospective, randomized, cross-over manikin study in which 24 certified rescuers performed CCs on a manikin placed on a firm standard mattress and a pressure-relieving mattress each with or without a backboard, there were no differences in the respective median CC depths.[14]

A subsequent meta-analysis of six studies including the two mentioned above found that when performing CCs on a manikin placed on a mattress or a bed, CC depth improved by 2.74 mm (95% CI: 1.19–4.28) when using a backboard compared to when not using a backboard.[7] This marginal difference meant that the International Liaison Committee on Cardiopulmonary Resuscitation was unable to make a recommendation for the use of a backboard in the international consensus which formed the basis of its international CPR guidelines.[7]

One conceivable reason for the inconsistent results of these studies is that the compression force applied by study participants to manikins on a mattress was not constant. Manikins used in CC training are assembled with a spring in the chest cavity in order to simulate the firmness of the thorax. Hooke's law states that the compression of a spring is directly proportional to the load; thus, if the study participants had all applied the same compression force to the manikin, their CC depths would have been identical. Given that the amount of mattress displacement is influenced by mattress firmness and backboard size, the different CC depths seen in previous studies may have been due to the lack of constant compression force among the respective study participants. Investigating purely the effects of mattress firmness and backboard size would therefore require that the compression force and its proportional CC depth be made constant.

In a study by Nishisaki et al. investigating the effectiveness of backboards, participants performed CCs on a manikin that provided real-time feedback in order to achieve constant CC depth, and mattress displacement was also measured simultaneously using an accelerometer.[8] After comparing CC depth on three different bed surfaces, namely, a stretcher, hospital bed, and ICU bed, the authors reported that the backboard significantly reduced mattress displacement only when it was used on the soft ICU bed.

The present study used a constant compression force of 250 N to investigate the effects of mattress firmness and backboard size on TCD. A force of 250 N is equivalent to a CC depth of 5 cm. Our study findings show that the inhibitory effect of the backboard on TCD became more pronounced as mattress firmness decreased. Given that TCD is determined by adding CC depth to mattress displacement, and given that our study maintained a constant CC depth, our findings on TCD were similar to those reported by Nishisaki et al.[8]

2. Backboard thickness

While the literature does contain reports on backboard thickness and density,[8,9] these studies also used different backboard sizes and therefore did not involve a comparison purely of backboard thicknesses. Moreover, while backboards are effective in reducing mattress displacement, they must be able to withstand compression-induced deformation in order to do so. The ability of a backboard to withstand deformation is determined not only by its density but also by its Young's modulus. The backboard material was modeled based on the Young's modulus of commonly used plastic materials. Because mechanical behavior in this context is primarily determined by stiffness rather than material type, backboards with similar Young's modulus, including wood-based materials, are expected to exhibit comparable performance. The simulations performed in the present study used a Young's modulus of 8.0×10^3 MPa for the backboard, based on the value for actual wood, and the simulation results showed that TCD was not affected at a backboard thickness of ≥7 mm.

3. Backboard size

A previous manikin study using mechanical compression to achieve a TCD of 5 cm found that a large backboard (86 cm ×50 cm) yielded a significantly greater CC depth than that of a small backboard (56 cm × 43cm).[9] However, the TCD of 5 cm used in this study was based on the combined mattress displacement and depth of CCs and therefore did not adhere to the definition of 5 cm CC depth recommended in guidelines.

A previous study in which participants performed CCs with real-time feedback in order to achieve an appropriate CC depth found that a narrow backboard (457 mm × 1826 mm) could reduce mattress displacement to a greater extent than a wide backboard (635 mm × 1508 mm), although the difference was marginal at 4.7% versus 6.6%.[15]

The present study also used a constant CC force in order to ensure appropriate CC depth, and simulations were performed while varying the backboard length from 40–80 cm and the backboard width from 40–60 cm. TCD tended to decrease with increasing backboard width and length, but the difference was ≤7 mm. When the backboard surface area exceeded 3500 cm^2, a ceiling effect occurred, with any further increases in surface area yielding only a limited effect on TCD. This ceiling effect suggests that excessively large backboards may not provide proportional mechanical benefit and may compromise practicality in clinical settings.

As larger and heavier backboards are inherently more difficult to maneuver, a thickness of 1 cm, length of 70 cm, and width of 50 cm would be sufficiently effective when manufacturing a backboard with the same Young’s modulus as that of wood.

Limitations

The present study has several limitations. The 3D analysis was performed on human chest CT images, and the findings were used to construct a computational model of the thorax using FEA. Because the thorax model was constructed from CT data of a single healthy adult male, the absolute values of TCD should not be directly generalized. However, the primary contribution of this study lies in demonstrating relative trends in response to continuous changes in mattress firmness and backboard dimensions, which are expected to be qualitatively robust across individuals. The role of individual differences in determining the relationship between sternal loading and CC depth has previously been demonstrated in a cadaver study.[10] As such, the trends observed in the present study are clearly not applicable to all patients. Also, although cardiac arrest patients are most frequently elderly, the model was constructed using CT scans of younger adult who did not have any deformities.

The present study sought to investigate how mattress firmness and backboard size affect TCD by conducting a simulation with a constant CC depth achieved by maintaining a constant compression force. However, when rescuers perform CCs, they may subconsciously reduce their compression force if they perceive that the TCD is too great. In other words, compression force and TCD may influence one other, in which case the conditions of the present study with compression force kept constant would not be representative of actual clinical conditions.

Conclusions

Using a backboard enabled a decrease in TCD compared with not using a backboard. Moreover, this decrease in TCD was more pronounced on a soft mattress. TCD tended to decrease with increasing backboard width and length, but the difference was marginal and thus was regarded as a ceiling effect. As larger and heavier backboards are inherently more difficult to maneuver, a thickness of 1 cm, length of 70 cm, and width of 50 cm would be sufficiently effective when manufacturing a backboard with the same firmness as that of wood.

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Data availability Data used in this paper are available from the corresponding author upon request.

References

1. Okubo M, Komukai S, Andersen LW, Berg RA, Kurz MC, Morrison LJ, Callaway CW; American Heart Association's Get With The Guidelines—Resuscitation Investigators. Duration of cardiopulmonary resuscitation and outcomes for adults with in-hospital cardiac arrest: retrospective cohort study. BMJ. 2024 Feb 7;384:e076019. doi: 10.1136/bmj-2023-076019. Erratum in: BMJ. 2024 Apr 18;385:q900. doi: 10.1136/bmj.q900.

2. Vadeboncoeur T, Stolz U, Panchal A, Silver A, Venuti M, Tobin J, Smith G, Nunez M, Karamooz M, Spaite D, Bobrow B. Chest compression depth and survival in out-of-hospital cardiac arrest. Resuscitation. 2014 Feb;85(2):182-8. doi: 10.1016/j.resuscitation.2013.10.002. Epub 2013 Oct 12.

3. Perkins GD, Benny R, Giles S, Gao F, Tweed MJ. Do different mattresses affect the quality of cardiopulmonary resuscitation? Intensive Care Med. 2003 Dec;29(12):2330-2335. doi: 10.1007/s00134-003-2014-6. Epub 2003 Sep 20.

4. Tweed M, Tweed C, Perkins GD. The effect of differing support surfaces on the efficacy of chest compressions using a resuscitation manikin model. Resuscitation. 2001 Nov;51(2):179-83. doi: 10.1016/s0300-9572(01)00404-x.

5. Sainio M, Hellevuo H, Huhtala H, Hoppu S, Eilevstjønn J, Tenhunen J, Olkkola KT. Effect of mattress and bed frame deflection on real chest compression depth measured with two CPR

sensors. Resuscitation. 2014 Jun;85(6):840-3. doi: 10.1016/j.resuscitation.2014.03.009. Epub 2014 Mar 19.

6. Nishisaki A, Nysaether J, Sutton R, Maltese M, Niles D, Donoghue A, Bishnoi R, Helfaer M, Perkins GD, Berg R, Arbogast K, Nadkarni V. Effect of mattress deflection on CPR quality assessment for older children and adolescents. Resuscitation. 2009 May;80(5):540-5. doi: 10.1016/j.resuscitation.2009.02.006. Epub 2009 Apr 1.

7. Olasveengen TM, Mancini ME, Perkins GD, Avis S, Brooks S, Castrén M, Chung SP, Considine J, Couper K, Escalante R, Hatanaka T, Hung KKC, Kudenchuk P, Lim SH, Nishiyama C, Ristagno G, Semeraro F, Smith CM, Smyth MA, Vaillancourt C, Nolan JP, Hazinski MF, Morley PT; Adult Basic Life Support Collaborators. Adult Basic Life Support: 2020 International Consensus on Cardiopulmonary Resuscitation and Emergency Cardiovascular Care Science With Treatment Recommendations. Circulation. 2020 Oct 20;142(16_suppl_1):S41-S91. doi: 10.1161/CIR.0000000000000892. Epub 2020 Oct 21.

8. Nishisaki A, Maltese MR, Niles DE, Sutton RM, Urbano J, Berg RA, Nadkarni VM. Backboards are important when chest compressions are provided on a soft mattress. Resuscitation. 2012 Aug;83(8):1013-20. doi: 10.1016/j.resuscitation.2012.01.016. Epub 2012 Feb 4.

9. Cloete G, Dellimore KH, Scheffer C, Smuts MS, Wallis LA. The impact of backboard size

and orientation on sternum-to-spine compression depth and compression stiffness in a manikin study of CPR using two mattress types. Resuscitation. 2011 Aug;82(8):1064-70. doi: 10.1016/j.resuscitation.2011.04.003. Epub 2011 Apr 15.

10. Tomlinson AE, Nysaether J, Kramer-Johansen J, Steen PA, Dorph E. Compression force-depth relationship during out-of-hospital cardiopulmonary resuscitation. Resuscitation. 2007 Mar;72(3):364-70. doi: 10.1016/j.resuscitation.2006.07.017. Epub 2006 Dec 4.
11. Sainio M, Hellevuo H, Huhtala H, Hoppu S, Eilevstjønn J, Tenhunen J, Olkkola KT. Effect of mattress and bed frame deflection on real chest compression depth measured with two CPR sensors. Resuscitation. 2014 Jun;85(6):840-3. doi: 10.1016/j.resuscitation.2014.03.009. Epub 2014 Mar 19.
12. Olasveengen TM, Semeraro F, Ristagno G, Castren M, Handley A, Kuzovlev A, Monsieurs KG, Raffay V, Smyth M, Soar J, Svavarsdottir H, Perkins GD. European Resuscitation Council Guidelines 2021: Basic Life Support. Resuscitation. 2021 Apr;161:98-114. doi: 10.1016/j.resuscitation.2021.02.009. Epub 2021 Mar 24.
13. Andersen LØ, Isbye DL, Rasmussen LS. Increasing compression depth during manikin CPR using a simple backboard. Acta Anaesthesiol Scand. 2007 Jul;51(6):747-50. doi: 10.1111/j.1399-6576.2007.01304.x. Epub 2007 Apr 10.

14. Putzer G, Fiala A, Braun P, Neururer S, Biechl K, Keilig B, Ploner W, Fop E, Paal P. Manual versus Mechanical Chest Compressions on Surfaces of Varying Softness with or without Backboards: A Randomized, Crossover Manikin Study. J Emerg Med. 2016 Apr;50(4):594-600.e1. doi: 10.1016/j.jemermed.2015.10.002. Epub 2015 Nov 19.

15. Perkins GD, Kocierz L, Smith SC, McCulloch RA, Davies RP. Compression feedback devices over estimate chest compression depth when performed on a bed. Resuscitation. 2009 Jan;80(1):79-82. doi: 10.1016/j.resuscitation.2008.08.011. Epub 2008 Oct 25.

Figure legends

Fig. 1 Analysis model for cardiopulmonary resuscitation simulation and boundary conditions of the simulation model. These contact points define how compressive forces applied to the sternum are transmitted to the mattress through the thorax, forming the mechanical basis for subsequent analysis of mattress displacement and TCD.

a, b. The circles in the figure are the points of contact between the thorax model and the mattress.

c. The thorax model was placed on the surface where the skin plate, backboard, and mattress were tie-coupled.

d. The two corners of the mattress, indicated by circles, were fully fixed.

Fig. 2 Load-displacement diagram.

This nonlinear load–displacement relationship is consistent with previous cadaveric studies and supports the physiological validity of the thorax model used in this simulation.

Fig. 3 a. Total compression depth with and without a backboard.

Solid lines indicate values without the backboard and dashed lines indicate values with the backboard.

b. Effect of backboard thickness.

From the top to bottom line, the total compression depth is shown for backboard thicknesses of 5 mm, 7 mm, 8 mm, 10 mm, and 20 mm, where the width is 50 cm and the length is 70 cm.

c. Effect of backboard length.

From the top to bottom line, the total compression depth is shown for backboard lengths of 40 cm, 50 cm, 60 cm, 70 cm, and 80 cm, where the thickness is 10 mm and the width is 50 cm.

d. Effect of backboard width.

From the top to bottom line, the total compression depth is shown for backboard widths of 40 cm, 50 cm, and 60 cm, where the thickness is 10 mm and the length is 60 cm.

The progressive flattening of the curves indicates that further increases in backboard thickness or dimensions result in only marginal additional reductions in TCD, suggesting a ceiling effect.

The shaded region indicates the range of mattress stiffness commonly used in clinical settings (Young's modulus: 10–13 kPa).

W width; *L* length

Fig. 4 Contour plot showing total compression depth when varying the length and width of backboard. When the backboard surface area exceeds approximately 3500 cm², further enlargement provides limited mechanical benefit, indicating a practical upper threshold for effective backboard dimensions.

a. air mattress (Hill-rom) [10 kPa].

b. mattress (Muranaka NST-2) [13 kPa].

Fig. 1

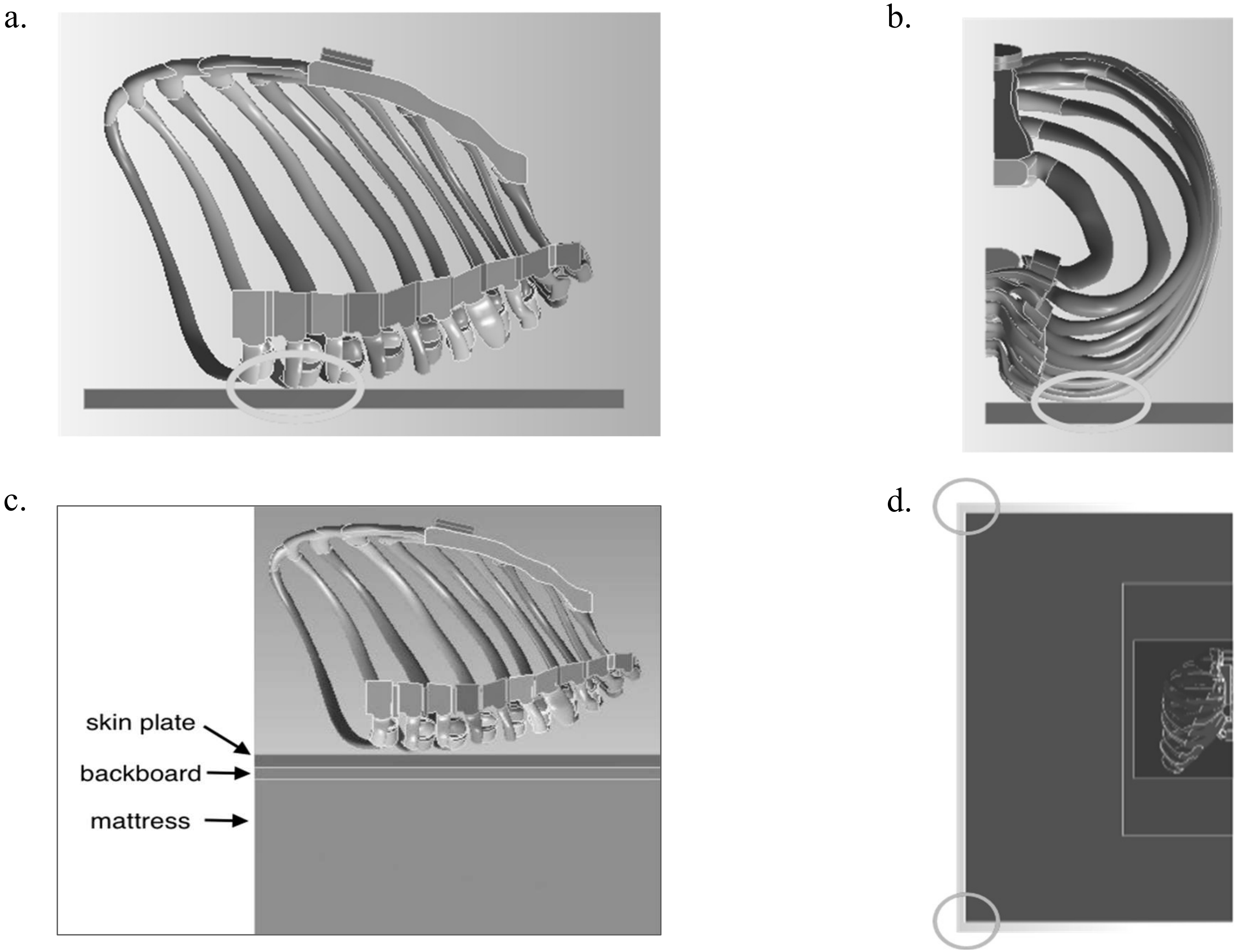


Fig. 2

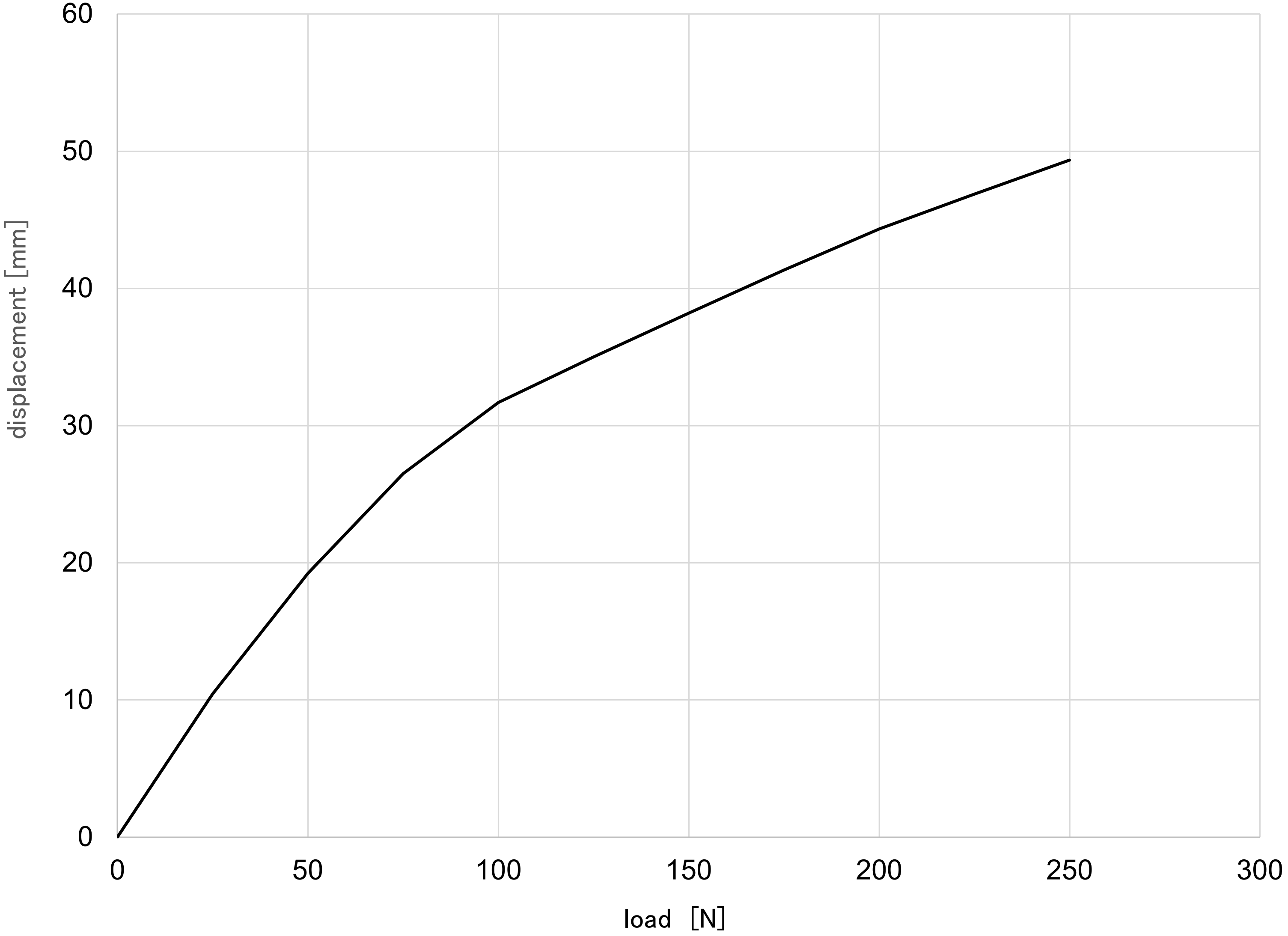

60
50
40
30
20
10
0
displacement [mm]
0
50
100
150
200
250
300
load [N]

Fig. 3

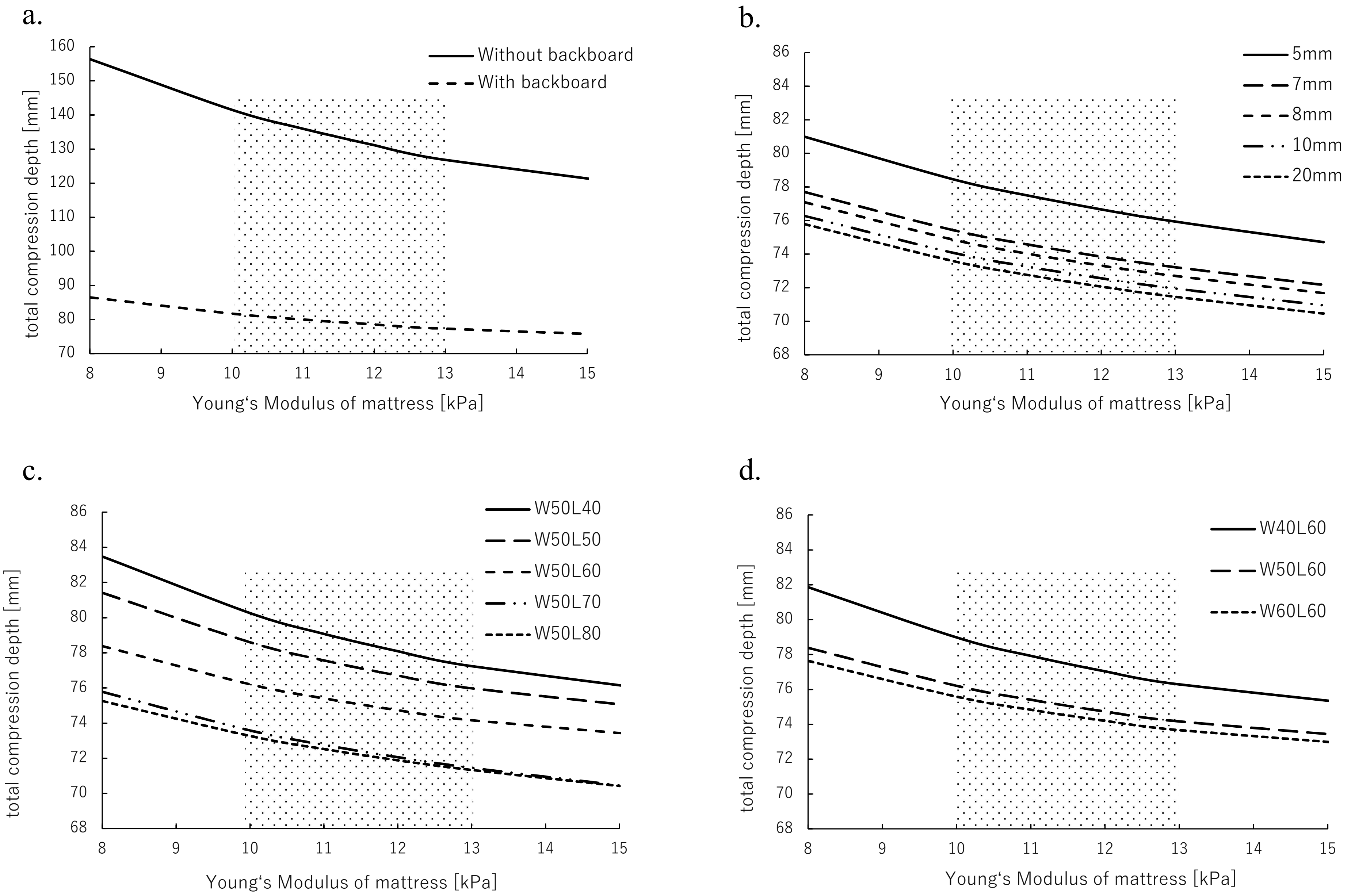
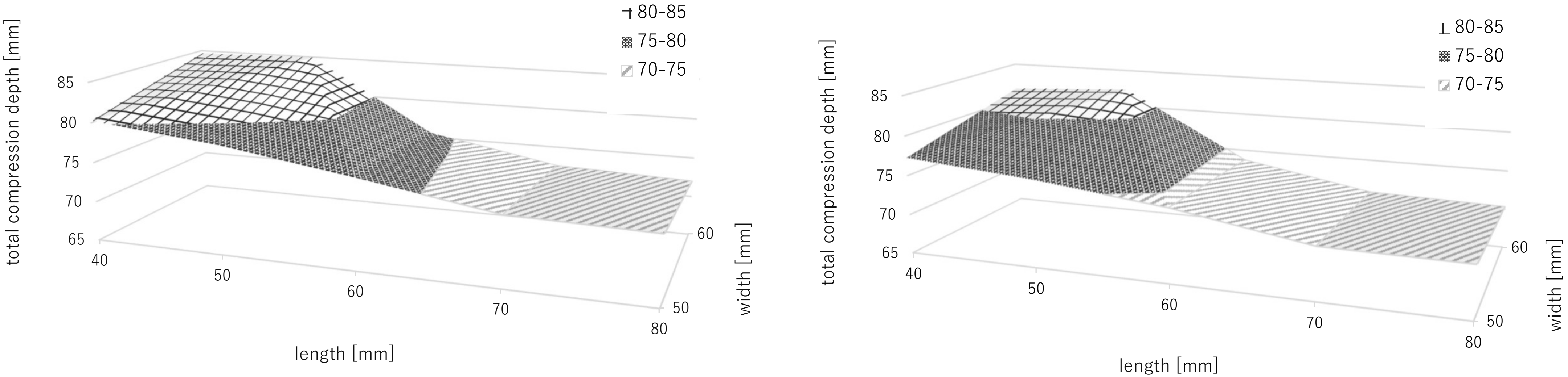

a.
160
150
140
130
120
110
100
90
80
70
8
9
10
11
12
13
14
15
total compression depth [mm]
Young‘s Modulus of mattress [kPa]
Without backboard
With backboard
b.
86
84
82
80
78
76
74
72
70
68
total compression depth [mm]
Young‘s Modulus of mattress [kPa]
5mm
7mm
8mm
10mm
20mm
c.
total compression depth [mm]
Young‘s Modulus of mattress [kPa]
W50L40
W50L50
W50L60
W50L70
W50L80
d.
total compression depth [mm]
Young‘s Modulus of mattress [kPa]
W40L60
W50L60
W60L60

Fig. 4



a. [10 kPa]

b. [13 kPa]

Table 1 Young‘s modulus, Poisson's ratio, bulk modulus, and shearing modulus

Part	Young‘s modulus E［MPa］	Poisson's ratio ν	Bulk modulus K［MPa］	Shearing modulus G［MPa］
Mattress		0.01		
Bone	12.0×10^3	0.30	10^4	4.62×10^3
Intervertebral disc	10.0	0.40	6.68	3.57
Backboard	8.0×10^3	0.35	8.89×10^3	2.96×10^3
Skin and muscles	0.3	0.40	0.50	0.11
Rib cartilage	25.0	0.35	27.78	9.26
Ligaments	3.0	0.45	10.00	1.03

Table 2 Mattress firmness

mattress type	Young‘s modulus
mattress (Muranaka NST-2)	13 kPa
air mattress (Cococia Yuki Series)	12 kPa
urethane mattress	11 kPa
air mattress (Hillrom)	10 kPa