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Research article

Effect of thoracic stiffness on chest compression performance - A prospective randomized crossover observational manikin study

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ABSTRACT

Introduction: Human thoracic stiffness varies and may affect the performance during external chest compression (ECC). The Extra Compression Spring Resusci® QCPR Anne manikin is a high-fidelity training model developed for ECC training that can account for varying levels of thoracic stiffness. The aim of this study was to use this training model to investigate the effects of thoracic stiffness on ECC biomechanics and qualities.

Methods: Fifty-two participants performed standard ECC on the manikin with different thoracic springs to simulate varying levels of thoracic stiffness. The MatScan Pressure Measurement system was used to investigate the ECC pressure and force distribution.

Results: The hard spring group's performance had a better complete recoil ratio (90.06 ± 24.84% vs. 79.75 ± 32.17% vs. 56.42 ± 40.15%, $p < 0.001$ at second minute), but was more inferior than the standard and soft spring groups in overall quality, ECC depth (34.17 ± 11.45 mm vs. 41.25 ± 11.42 mm vs. 51.88 ± 7.56, $p < 0.001$ at second minutes), corrected depth ratio, and corrected rate ratio. The hard spring group had less radial-ulnar peak pressure difference (kgf/cm^2) than the other two groups (−0.28 ± 0.38 vs. −0.30 ± 0.43 vs. −0.47 ± 0.34, $p = 0.01$), demonstrating that more symmetrical pressure was applied in the hard spring group. The soft spring group had better ECC depth, corrected depth ratio, corrected rate ratio, and overall quality, but its performance in complete recoil was inferior, and unbalanced pressure was more liable to cause injury. Hard springs caused operator fatigue easily.

Conclusion: The thoracic stiffness greatly affected the performance of ECC. Our findings provided information for more effective ECC practices and training.

1. Introduction

Thoracic stiffness has been shown to be an important factor affecting the quality of chest compressions clinically [1, 2]. A 2007 study concluded that differences in thoracic stiffness affected effective depth of external chest compressions (ECC) [2]. However, that study set the effective chest compression depth to be greater than 3.8 cm, and there was no study of recoil according the guideline at the time [2].

Since 2010, cardiopulmonary resuscitation (CPR) guidelines have recommended deeper (5–6 cm) and faster (100–120 per min) ECC with complete recoil and minimal compression interruptions. The 2015 and 2020 advanced cardiac life support (ACLS) guidelines reiterate these recommendations [3, 4]. The increase in compression depth and full recoil have been greatly emphasized to achieve high-quality CPR [3, 4].

Previous biomechanical analyses of the constant peak displacement (CPD) model and constant peak force (CPF) model during CPR have shown that the ideal chest compression quality is related to the stiffness of the back support, the compression rate, and the thoracic stiffness of the patients [5, 6].

The simulation results of Jiang et al. in 2014 showed that in the CPF model, the patient's thoracic stiffness had a significant impact on the quality of chest compression depth [7]. Using the CPF model, Dellimore et al. found that the depth of chest compression was highly dependent upon thoracic stiffness [6]. In the CPF model, patients with greater

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thoracic stiffness (≥100 N cm(−1)), required a higher chest compression force to reach the compression depth required by the ACLS guidelines, but potentially increased the risk for severe chest injuries and blunt abdominal injuries [8]. Therefore, the CPD technique is preferred to maintain CPR quality regardless of thoracic stiffness [6, 7].

Current CPR guidelines presume that effective compression depth can be reliably achieved. However, previous studies have shown that chest wall stiffness, potentially affecting compression depth, varies greatly from person to person and is affected by factors such as age, sex, and body mass index (BMI) [1, 2, 9, 10]. Thoracic stiffness can play a role in the occurrence of rib fractures during chest compression [11]. Excessive force or unbalanced distribution often causes physical damage, such as rib fractures, sternum fractures or liver ruptures [6, 12, 13, 14].

While training manikins can be valuable training tools, their fixed chest wall stiffness is unable to simulate the variability in chest wall stiffness found in actual patients.

The Extra Compression Spring Resusci Anne® QCPR (Laerdal Medical, Wappingers Falls, NY). manikin was developed in order to account for this limitation [15]. This manikin has more realistic chest characteristics due to the wide range in chest stiffness and has the potential to become an important tool for CPR research and training [15].

Although the Resusci Anne QCPR manikin is readily available for training, the use of the extra compression springs as a research field has not been well explored. The aim of this study was to investigate the effects of different thoracic stiffness on ECC biomechanics and qualities. This study may lead to a better understanding of how thoracic stiffness affects CPR training and clinical practice.

2. Methods

2.1. Setting and design

We conducted a crossover, randomized-to-order design study at the National Cheng Kung University Hospital (NCKUH) from January to December 2019. Fifty-two participants included experienced emergency medical technicians from the ambulance team of the Fire Bureau and doctors and nurses from NCKUH. All participants were healthy without muscular skeletal or neurological injury during the past six months. Each participant performed adult ECC according to the 2015 ACLS guidelines [3]. This study was approved by the ethics review board of National Cheng Kung University Hospital (ethical approval number: NCKUH B-ER-105-418) and informed consent forms were signed for all participants.

The participants performed ECC on the Extra Compression Spring Resusci® Anne manikin. This manikin has three kinds of springs (the elasticity coefficients were 0.6 kg/mm, 0.9 kg/mm and 1.2 kg/mm), which are referred to as soft, standard and hard thoracic springs [16]. Study participants were able to practice and familiarize themselves with the manikin with the different springs prior to assessment.

Rescuers were placed in a kneeling position to the right of the manikin with their left hand down. Each participant performed 2 min of ECC on the manikin with three different levels of spring stiffness. These measurements were randomly ordered, and the participants had adequate rest of more than 30 min between assessments. The participants performed compression-only cardiopulmonary resuscitation, which was administered at a rate of least 100 compressions per minute and 5–6 cm in depth.

2.2. Data collection

The Extra Compression Spring Resusci® Anne manikin (Laerdal Medical, Wappingers Falls, NY) was connected to the Laerdal PC Skill Reporting System (QCPR) which allowed us to record the depth, rate, recoil and effectiveness of chest compression. The ECC data were recorded every minute.

The manikin was also equipped with a Force Sensing Array® system (*MatScan*–Pressure Measurement System Evolution Based (Tekscan Inc, South Boston, USA)). Which allowed us to measure the distribution of force and pressure. The MatScan system has 2288 pressure sensors per cm^2 and a spatial resolution of 1.4 sensors per cm^2. It can record at a sampling frequency of 30 Hz. This pressure pad is flexible and only 0.1 mm thick. This system has high accuracy and good reliability [2, 9, 10, 17, 18].

Blood pressure and heart rate before and after each ECC session were measured in each of the study participants, along with ratings of perceived exertion (RPE), using a modified Borg scale of 1–10 [19]. Visual analog scales were used to rate the level of discomfort during each ECC session.

2.3. Data analysis

G*Power [20, 21] was used to determine a minimum total sample size of 50 in order to achieve an alpha level of 0.05, a power of 0.90, and an effect size of 0.21 derived from our pilot study of 10 participants. We used repeated measures ANOVA and t tests, and the level of statistical significance was set at $p < 0.05$. This statistical analysis was performed using SPSS version 20.

3. Results

A total of 52 participants were involved in this study, including 24 men and 28 women. The average age was 30.3 ± 5.3 years old, the

Table 1. Chest Compression Quality of the three spring types during first minute and second minute of CPR.

ECC performance		Hard spring	Standard spring	Soft spring	p-value
		Mean ± SD	Mean ± SD	Mean ± SD	
ECC quality (%)	1 min	39.73 ± 36.91†‡	65.87 ± 35.03†¶	89.79 ± 16.95‡¶	<0.001*
	2 min	26.29 ± 33.00†‡	48.31 ± 40.54†¶	81.96 ± 23.58‡¶	<0.001*
Compression depth (mm)	1 min	37.67 ± 10.81†‡	45.48 ± 9.76†¶	54.73 ± 5.64‡¶	<0.001*
	2 min	34.17 ± 11.45†‡	41.25 ± 11.42†¶	51.88 ± 7.56‡¶	<0.001*
Correct depth (%)	1 min	17.10 ± 31.91†‡	42.88 ± 41.83†¶	79.75 ± 33.61‡¶	<0.001*
	2 min	13.58 ± 30.69†‡	28.38 ± 39.31†¶	64.81 ± 41.72‡¶	<0.001*
Compression rate (per min)	1 min	115.44 ± 8.47†‡	112.42 ± 6.72†	111.46 ± 7.16‡	0.001*
	2 min	116.25 ± 10.75†‡	112.83 ± 9.17†	111.46 ± 8.05‡	<0.001*
Correct rate (%)	1 min	69.21 ± 35.26†‡	82.06 ± 25.14†	81.56 ± 22.44‡	0.021*
	2 min	63.12 ± 38.27‡	71.12 ± 29.74	76.92 ± 29.30‡	0.040*
Complete recoil (%)	1 min	86.12 ± 25.12†‡	71.79 ± 35.07†¶	56.88 ± 39.62‡¶	<0.001*
	2 min	90.06 ± 24.84†‡	79.75 ± 32.17†¶	56.42 ± 40.15‡¶	<0.001*

ECC: External Chest Compression.
*$p < 0.05$, significantly different according to repeated measures ANOVA.
†‡¶, significant difference between the two groups with the same symbols.

average height was 166.9 ± 9.16 cm, and the average body weight was 61.9 ± 13.1 kg. There were 50 right-handed dominant people and 2 left-handed dominant people. All participants were professional health care workers or emergency medical technicians.

3.1. Quality of chest compressions

The measures of chest compression quality from the Laerdal PC Skill Reporting System are listed in Table 1.

The overall ECC quality scored by the QCPR system was significantly different in the hard-, standard- and soft-spring groups in the first minute (39.73 ± 36.91 versus 65.87 ± 35.03 versus 89.79 ± 16.95, respectively, $p < 0.001$*) and in the second minute (26.29 ± 33.00 versus 48.31 ± 40.54 versus 81.96 ± 23.58, $p < 0.001$*).

The hard-spring group, compared with the standard- and soft-spring groups, had a lower compression depth in the first minute (37.67 ± 10.81 mm versus 45.48 ± 9.76 mm versus 54.73 ± 5.64 mm, $p < 0.001$*) and in the second minute (34.17 ± 11.45 mm versus 41.25 ± 11.42 mm versus 51.88 ± 7.56, $p < 0.001$*). The hard-spring group also had a lower correct depth ratio than the standard- and soft-spring groups in the first minute (17.10 ± 31.91% versus 42.88 ± 41.83% versus 79.75 ± 33.61%, $p < 0.001$*) and second minute (17.10 ± 31.91% versus 42.88 ± 41.83% versus 79.75 ± 33.61%, $p < 0.001$*).

The compression rate was higher in the hard-spring group than in the standard- and soft-spring groups in the first minute (115.44 ± 8.47 beats/min versus 112.42 ± 6.72 beats/min versus 111.46 ± 7.16 beats/min, $p = 0.001$*) and in the second minute (116.25 ± 10.75 beats/min versus 112.83 ± 9.17 beats/min versus 111.46 ± 8.05 beats/min, $p < 0.001$*). However, the hard-spring group had a lower correct rate ratio than the standard- and soft-spring groups in the first minute (69.21 ± 35.26% versus 82.06 ± 25.14% versus 81.56 ± 22.44%, $p = 0.021$*) and second minute (63.12 ± 38.27% versus 71.12 ± 29.74% versus 76.92 ± 29.30%, $p = 0.040$*).

The hard-spring group was more likely to achieve complete recoil than the standard- and soft-spring groups in the first minute (86.12 ± 25.12% versus 71.79 ± 35.07% versus 56.88 ± 39.62%, $p < 0.001$*) and second minute (90.06 ± 24.84% versus 79.75 ± 32.17% versus 56.42 ± 40.15%, $p < 0.001$*).

3.2. Peak force of chest compressions

Peak force was significantly different in both the first and second minute (Table 2). The hard-spring group demonstrated the highest peak force while the soft-spring group had the lowest peak force in the first minute (67.91 ± 14.87 kgf versus 47.88 ± 16.18 kgf, $p < 0.001$*) and second minute (62.70 ± 15.62 kgf versus 44.80 ± 16.20 kgf, $p < 0.001$*).

We divided the force distributions into ulnar (cranial) and radial (caudal) areas based on the compression center point of operator's left hand, which was on the manikin. We used the radial-ulnar force distribution to determine whether the direction of force was perpendicular to the chest wall of the manikin. The radial-ulnar peak force differences were significantly different between the first minute and the second minute. Hard-springs showed the smallest difference in radial-ulnar peak force differences while soft-springs showed the largest difference in the first minute (−4.56 ± 18.74 kgf versus -16.95 ± 16.15 kgf, $p < 0.001$*), and second minute (−4.15 ± 19.35 kgf versus -17.47 ± 16.90 kgf, $p < 0.001$*).

3.3. Peak pressure of chest compressions

The peak pressures in the three groups were significantly different. Peak pressure increased as spring stiffness increased. (2.05 ± 0.53 kgf/cm^2 versus 1.79 ± 0.54 kgf/cm^2 versus 1.50 ± 0.60 kgf/cm^2, $p = 0.037$*).

We also divided the pressure distributions into ulnar (cranial) and radial (caudal) areas based on the compression center point of operator's left hand, which was on the manikin. The radial-ulnar peak pressure difference was significantly different, depending on spring stiffness. This difference decreased as spring stiffness increased (−0.28 ± 0.38 kgf/cm^2 versus -0.47 ± 0.34 kgf/cm^2, $p = 0.010$*).

3.4. Physiological parameters before and after external chest compression

Physiological parameters were assessed in the study participants included systolic blood pressure, diastolic blood pressure and heart rate (Table 3). There were no significant differences among these three groups before and after ECC. However, in the second minute, the systolic blood pressure and heart rate were slightly increased compared to the first minute.

Table 2. Compression force and pressure administered through three spring types during first minute and second minute of CPR.

Force and pressure		Hard spring	Standard spring	Soft spring	p value[b]
		Mean ± SD	Mean ± SD	Mean ± SD	
Peak Force (kgf)	First minute	67.91 ± 14.87†‡	52.91 ± 12.66‡¶	47.88 ± 16.18†¶	<0.001*
	Second minute	62.70 ± 15.62†‡	49.88 ± 12.81‡¶	44.80 ± 16.20†¶	<0.001*
Radial-ulnar peak force difference (Kgf)	First minute	-4.56 ± 18.74†‡	-9.65 ± 17.44‡¶	-16.95 ± 16.15†¶	<0.001*
	Second minute	-4.15 ± 19.35†‡	-8.78 ± 15.91‡¶	-17.47 ± 16.90†¶	<0.001*
Peak pressure (kgf/cm2)	Two minutes	2.05 ± 0.53†‡	1.79 ± 0.54‡¶	1.50 ± 0.60†¶	0.037*
Radial-ulnar peak pressure difference (kgf/cm2)	Two minutes	-0.28 ± 0.38†	-0.30 ± 0.43¶	-0.47 ± 0.34†¶	0.010*

*$p < 0.05$, significantly different according to repeated measures ANOVA.
†‡¶, significant difference between the two groups with the same symbols.

Table 3. Physiological parameters before and after for the three spring types.

Physiological parameters		Hard spring	Standard spring	Soft spring	p-value
		Mean ± SD	Mean ± SD	Mean ± SD	
Systolic blood pressure (mmHg)	Before	119.44 ± 14.33	118.23 ± 13.80	119.33 ± 14.71	0.892
	After	129.52 ± 15.52	131.04 ± 16.76	130.75 ± 16.20	0.879
Diastolic blood pressure (mmHg)	Before	81.35 ± 9.37	78.98 ± 9.75	79.15 ± 10.14	0.389
	After	79.58 ± 9.00	78.67 ± 9.50	77.44 ± 9.14	0.496
Heart rate (beat/min)	Before	78.12 ± 12.00	79.75 ± 12.38	79.77 ± 12.91	0.739
	After	95.27 ± 18.82	100.46 ± 19.16	100.73 ± 17.20	0.237

*$p < 0.05$, significantly different according to repeated measures ANOVA.
†‡¶, significant difference between the two groups with the same symbols.

Table 4. Perceived fatigue and discomfort of three groups.

Fatigue \Three groups		Hard spring	Standard spring	Soft spring	p-value
		Mean ± SD	Mean ± SD	Mean ± SD	
Fatigue (0–10)		6.05 ± 2.47†‡	5.27 ± 2.26‡¶	4.09 ± 2.27†¶	0.002*
Discomfort (0–10)	Wrist	3.54 ± 3.14	2.92 ± 2.56	1.62 ± 2.25	0.323
	Hand	4.42 ± 2.98	3.22 ± 3.14	1.38 ± 1.96	0.330
	Low back	1.92 ± 2.68	1.30 ± 2.24	1.04 ± 1.67	0.739
	Overall	6.05 ± 2.20†‡	4.93 ± 2.33‡¶	4.07 ± 2.04†¶	0.050*

*$p < 0.05$, significantly different according to repeated measures ANOVA.
†‡¶, significant difference between the two groups with the same symbols.

3.5. Perceived exertion ratings, fatigue and discomfort

A modified Borg scale with ratings from 1 to 10 was used to assess fatigue and discomfort. Higher spring stiffness was associated with significantly higher fatigue and overall discomfort scores. Although the participants reported higher levels of discomfort in the hand, wrist and low back when using stiffer springs, the differences were not statistically significant (Table 4).

4. Discussion

Our study shows how differences in thoracic stiffness can greatly affect CPR performance. Prior studies have focused upon the relationship between thoracic stiffness and ECC depth [1, 2]. As CPR guidelines have evolved, there is increasing awareness on the importance of chest recoil and compression speed [3, 4]. In addition to ECC depth, our study found that the depth accuracy, speed, compression speed accuracy, the recoil ratio, and the radial-ulnar peak force differences during ECC were significantly impacted based on differences in the thoracic stiffness of the manikin.

Based on our data recorded from the QCPR system, the quality of ECC was greatest when utilizing the soft springs for manikin chest stiffness, followed by the standard stiffness springs. Participants had the lowest performance when performing ECC with the hard thoracic stiffness springs. Better compression depths and correct depth ratios were also noted with the soft thoracic stiffness springs. Previous research has also shown that compression rate can affect the efficacy of ECC [22] Faster average compression rate was observed in our study with the hard-springs, but participants were not able to achieve correct compression rate as consistently compared to the soft-springs, and also had the lowest recoil ratios.

These findings are not surprising, since increased chest stiffness can increase the difficulty of the chest compressions, resulting in insufficient ECC depth. To compensate, additional force is needed, as reflected by the higher peak forces and pressures with the hard-springs. Although the hard-springs were associated with a higher rate of chest compressions, there was more variability in chest compression rate. Higher spring-stiffness was also associated with better recoil ratios and smaller.

4.1. Radial-ulnar peak force and peak pressure differences

Radial-ulnar peak force/pressure difference is an important concern. When the force is the same, the deviation of the force diminishes the performance of chest compressions [12, 23]. When the force deviation is larger, more force is needed to reach adequate depth, and a larger force may cause more damages, such as spinal injuries, rib fractures, sternal fractures, liver laceration or spleen rupture [13, 14]. Therefore, in addition to direct application of force may cause injury to soft thoracic stiffness patients, compared with hard, standard group, the force deviation may aggravate injuries in this group.

Besides, high-fidelity manikins are a useful tool in CPR education and training, but we usually only practice on Annie manikins with standard thoracic stiffness. However, clinically, everyone's chest stiffness is not the same. Previous studies have shown that experienced health care providers can very consistently confirm the stiffness of the manikin's chest that they feel when they perform chest compressions [24]. In the simulation environment, the performers provided adequate depth (3–5 cm) of chest compressions with differences in thoracic stiffness, based on the requirements of the 2005 guidelines, even on the harder chest [25]. Tomlinson et al. measured the depth and strength of chest compressions during CPR in 91 patients with out-of-hospital cardiac arrest and found that most of them could achieve a sufficient compression depth (3–5 cm) when the force was less than 50 kg [2]. However, these studies are based on the 2005 ACLS guideline with a depth of 1.5–2 inches instead of the current guideline suggesting a depth greater than 2 inches (5 cm) [3, 4, 26]. In our research, it was shown that a depth of 3–5 cm was reached in the conditions with differences in thoracic stiffness, but the increase in thoracic stiffness will affect whether the depth can reach more than 5 cm.

There are some limitations. First, we did not evaluate ventilation factors during CPR because the study focused only on the difference in chest compressions with differences in thoracic stiffness. Second, this was a manikin simulation study and further study is need to extrapolate to real-world clinical conditions. Third, clinical outcomes were not evaluated. Fourth, the study assessed performance only in 2-minute ECC conditions, and therefore, the results with longer durations of ECC remain unknown. The difference across these three groups might be more significant over longer durations.

5. Conclusion

Our research shows that thoracic stiffness greatly affects the chest compression performance. Participants in the hard spring group did not perform as well as those in the standard and soft spring group in overall quality, ECC depth, correct depth ratio, correct rate ratio, and fatigue. However, they did achieve a better complete recoil ratio. The hard spring group showed less radial-ulnar peak pressure difference, reflecting more balanced pressure during ECC. The soft spring group had better ECC depth, correct depth ratio, correct rate ratio and overall quality, but performed worse on recoil with less balanced pressure which might increase risk for injury. Our findings will provide information for more effective ECC practice and training.

Declarations

Author contribution statement

Chia-Lung Kao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jui-Yi Tsou: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ming-Yuan Hong and Chih-Jan Chang: Performed the experiments.

Fong-Chin Su: Conceived and designed the experiments.

Chih-Hsien Chi: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] K.G. Gruben, A.D. Guerci, H.R. Halperin, A.S. Popel, J.E. Tsitlik, Sternal force-displacement relationship during cardiopulmonary resuscitation, J. Biomech. Eng. 115 (1993) 195–201.
[2] A.E. Tomlinson, J. Nysaether, J. Kramer-Johansen, P.A. Steen, E. Dorph, Compression force-depth relationship during out-of-hospital cardiopulmonary resuscitation, Resuscitation 72 (2007) 364–370.
[3] G.D. Perkins, A. Travers, R.A. Berg, et al., Basic life support chapter collaborators., Part 3: adult basic life support and automated external defibrillation: 2015 international consensus on cardiopulmonary resuscitation and emergency cardiovascular care science with treatment recommendations, Resuscitation 95 (2015) e43–69.
[4] A.R. Panchal, J.A. Bartos, J.G. Cabañas, et al., Adult basic and advanced life support writing group. Part 3: adult basic and advanced life support: 2020 American heart association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care, Circulation 142 (2020) S366–S468.
[5] B.C. Boe JM, Mechanics of cardiopulmonary resuscitation performed with the patient on a soft bed vs a hard surface, Acad. Emerg. Med. 6 (1999) 754–757.
[6] S.C. Dellimore KH, Optimal chest compression in cardiopulmonary resuscitation depends upon thoracic and back support stiffness, Med. Biol. Eng. Comput. 50 (2012) 1269–1278.
[7] B. Jiang, H. Mao, L. Cao, K.H. Yang, Application of an anatomically-detailed finite element thorax model to investigate pediatric cardiopulmonary resuscitation techniques on hard bed, Comput. Biol. Med. 52 (2014) 28–34.
[8] K.H. Dellimore, C. Scheffer, A modeling approach to the effects of force guided versus depth guided compression during cardiopulmonary resuscitation on different chests and back support surfaces, Resuscitation 84 (2013) 837–842.
[9] J.E. Tsitlik, M.L. Weisfeldt, N. Chandra, M.B. Effron, H.R. Halperin, H.R. Levin, Elastic properties of the human chest during cardiopulmonary resuscitation, Crit. Care Med. 11 (1983) 685–692.
[10] X. Shi, L. Cao, M.P. Reed, J.D. Rupp, C.N. Hoff, J. Hu, A statistical human rib cage geometry model accounting for variations by age, sex, stature and body mass index, J. Biomech. 18 (47) (2014) 2277–2285.
[11] R.S. Hoke, D. Chamberlain, Skeletal chest injuries secondary to cardiopulmonary resuscitation, Resuscitation 63 (2004) 327–338.
[12] M. Baubin, J. Kollmitzer, A. Pomaroli, et al., Force distribution across the heel of the hand during simulated manual chest compression, Resuscitation 35 (1997) 259–263.
[13] S.S. Azuma, E.T. Mashiyama, C.I. Goldsmith, et al., Chest compression-induced vertebral fractures, Chest 89 (1986) 154–155.
[14] C. von Bary, S. Hohenester, J. Gaa, et al., Liver laceration associated with the use of a chest compression device, Resuscitation 80 (2009) 839.
[15] J.B. Nysaether, E. Dorph, I. Rafoss, P.A. Steen, Manikins with human-like chest properties–a new tool for chest compression research, IEEE Trans. Biomed. Eng. 55 (2008) 2643–2650.
[16] Information sheet: extra compression springs for Resusci Anne QCPR, Available at: http://cdn.laerdal.com/downloads/f2733/Resusci_Anne_QCPR_-_Extra_Springs_information_Nov-2013.pdf, 2013. Accessed Feb. 2, 2022.
[17] J.Y. Tsou, C.L. Kao, C.J. Chang, Y.F. Tu, F.C. Su, C.H. Chi, Biomechanics of two-thumb versus two-finger chest compression for cardiopulmonary resuscitation in an infant manikin model, Eur. J. Emerg. Med. 27 (2020) 132–136.
[18] J.Y. Tsou, C.L. Kao, M.Y. Hong, C.J. Chang, F.C. Su, C.H. Chi, How does the side of approach impact the force delivered during external chest compression? Am. J. Emerg. Med. 48 (2021) 67–72.
[19] G.A. Borg, Psychophysical bases of perceived exertion, Med. Sci. Sports Exerc. 14 (1982) 377–381.
[20] F. Faul, E. Erdfelder, A.G. Lang, A.G. Buchner, *Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences, Behav. Res. Methods 39 (2007) 175–191.
[21] F. Faul, E. Erdfelder, A. Buchner, A.G. Lang, Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses, Behav. Res. Methods 41 (2009) 1149–1160.
[22] J.M. Agostinucci, L. Weisslinger, N. Marzouk, et al., Relation between chest compression rate and depth: the ENFONCE Study, Eur. J. Emerg. Med. 28 (2021) 352–354.
[23] C.L. Kao, J.Y. Tsou, M.Y. Hong, C.J. Chang, C.H. Chi, Biomechanical analysis of force distribution in one-handed and two-handed adult chest compression: a randomised crossover observational study, Emerg. Med. J. 39 (2021) 353–356.
[24] N.A. Arbogast KB, S. Balasubramanian, et al., Expert clinical assessment of thorax stiffness of infants and children during chest compressions, Resuscitation 80 (2009) 1187–1191.
[25] K.-J.J. Ødegaard S, A. Bromley, H. Myklebust, J. Nysaether, L. Wik, P.A. Steen, Chest compressions by ambulance personnel on chests with variable stiffness: abilities and attitudes, Resuscitation 74 (2007) 127–134.
[26] ECC Committee, Subcommittees and Task Forces of the American Heart Association, American heart association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care, Circulation 112 (24 Suppl) (2005) IV1–IV203.