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RESEARCH ARTICLE

Modeling human movement and mechanics: thoracic cage

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ABSTRACT
Computer-generated models have revolutionized how reconstructions of violent events, such as police use of force, are both performed and visualized. Yet, many experts in the legal and forensic disciplines do not understand them at a level required to use them effectively or create credible arguments supporting their findings. Simply put, models are a simplification of reality. Hence, models permit human programmers to specify the simplified behavior of a system. Since model parameters dictate the system's behavior, the programmer must document and provide justification for the selection of model parameters. The model structure, together with the selected parameters, form the backbone supporting the forensic investigator's conclusions. This paper will begin with an overview of the usefulness of models in forensic investigations and follow with an example of how a model is constructed and applied in use of force cases. The selected cases are particularly relevant to incidents commonly encountered in law enforcement, frequently leading to litigation.

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RÉSUMÉ
La réalisation et la visualisation des reconstructions d'événements violents, tels que ceux générés par le recours aux forces policières, ont été révolutionnées par la modélisation par ordinateur. Toutefois, de nombreux experts dans des disciplines juridiques et médico-légales n'ont pas une connaissance suffisante pour leur bonne utilisation ou pour créer des arguments crédibles à l'appui de leurs conclusions. Concrêtement, les modèles sont une simplification de la réalité et permettent aux programmeurs humains de spécifier le comportement simplifié d'un système. Puisque les paramètres du modèle dictant le comportement du système, le programmeur se doit de documenter et de justifier la sélection des paramètres du modèle. La structure du modèle, ainsi que les paramètres sélectionnés, sont les piliers de l'argumentaire et sont primoridiaux aux conclusions des enquêtes des experts en science médico-légale. Cet article présente tout d'abord un aperçu de l'utilité des modèles dans les enquêtes médico-légales et ensuite un exemple de construction et d'application d'un modèle dans des cas d'usage de la force. Les cas présentés sont d'une grande pertinence pour les incidents couramment rencontrés dans le domaine de l'application de la loi par les forces policières, menant fréquemment à des litiges.

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Introduction

The ability of forensic investigation to pinpoint the mechanism of injury is often limited by the availability or quality of evidence necessary to draw conclusions. When the investigator cannot directly measure the forces or must determine the accuracy of differing accounts, biomechanical models can provide reliable estimates of forces and distinguish between different possible scenarios. A biomechanical model consists of a structure of linked body segments which undergo motion and deformation when forces are applied. Thus, estimated forces can be used to determine possible motions and deformations of body segments or, conversely, possible motions and deformations of body segments can be used to estimate forces. The validity of the model depends on the accuracy of its structure, which includes the geometry of the linked body segments and their physical properties, and the accuracy of its parameters. The parameters include the length and mass of body segments and the physical properties of body tissues, such as viscoelasticity. Biomechanical models have long been applied for prediction of injury in motor vehicle accidents, supplementing data acquired from crash test dummies and cadavers [1]. With advancing research, data on the mechanics of various tissues have accumulated, allowing for refinement and specialization of models. In this paper, we develop a model of the thoracic cage based on data obtained from cadaver studies of rib cage mechanics. We apply the model to a specific police arrest technique and discuss other possible applications of the model in forensic investigations.

Materials and methods

A biomechanical lumped parameter linear spring model of the thoracic cage was created, based on the results of experiments which characterized the mechanical properties of isolated ribs and the rib cage as a unit [2–5]. It was shown that ribs behaved much like springs and that when one rib was pushed, that adjacent ribs on both the same and opposite sides of the ribcage were also displaced, although by a smaller amount. Such coupled motion occurs because the ribs are mechanically linked through their attachments to the thoracic spine and the sternum. Consequently, the mechanical behaviour of the ribcage is something like a coil spring mattress, where the coils are linked. Depressing a single coil results in a larger region around the coil also being depressed, with the amount of depression decreasing with distance. The amount of coupling between ribs was measured in a study performed by Kindig *et al.* [3]. The results of those measurements, documented in Figure 21 of their paper, were used to create a model of the ribcage, designed to predict the movement of each rib when one or more ribs are pushed.

In the Kindig *et al.* [3] study each rib was displaced at a controlled rate by pushing either at the costo-chondral junction (red dot in Figure 1A) or on the bone, 5 cm lateral to the costo-chondral junction (green dot in Figure 1A). In each case, the resulting movement of adjacent ribs was measured at both the costo-chondral junction and bone locations. The amount that adjacent ribs moved relative to the controlled displacement provided a measure of the mechanical

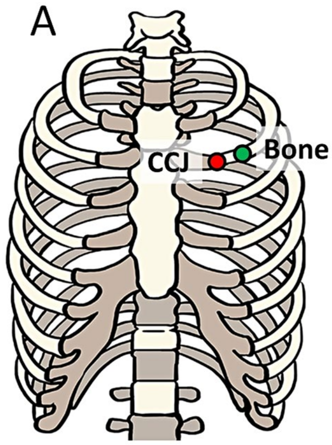

Figure 1. (A) Location of applied rib displacement at costo-chondral junction (CCJ, red) and bone (green), depicted for rib 2. (B) Illustration of ribs superior (S), inferior (I) and contralateral (C) to a loaded rib (L).

coupling between ribs. Because the ribs act like an array of parallel springs, mechanical coupling can be interpreted as sharing the load among all of the ribs. Consider the rib to which the displacement is applied, together with the adjacent inferior, superior and contralateral ribs, illustrated in Figure 1B as L, S, I and C, respectively. When a load is applied to rib L ribs S, I, and C undergo some displacement because of their coupling. Each rib bears a portion of the load which is proportional to the amount by which it is displaced. Kindig *et al.* [3] displaced ribs 1 to 9 individually and measured the resulting displacement of the superior (S), inferior (I) and contralateral (C) ribs. The relative displacements are plotted in Figure 21 of their paper [3]. Our thoracic cage model is constructed by considering each rib, in turn, as the loaded rib (L) and then reading the relative displacements for the corresponding S, I and C ribs from Figure 21 [3]. The relative displacements for the S, I, C and L ribs were then divided by the relative displacement for the L rib to obtain normalized displacements which are listed in Table 1. Since rib 10 was not tested by Kindig *et al.* [3], it was assumed to have the same values as rib 9.

In our model, Table 1 is a fixed structure which defines how the ribs are mechanically linked. It represents the fundamental mechanical structure of the thoracic cage which forms the basis of a computational model which can be applied to specific scenarios. To illustrate how a computational model is constructed for a specific scenario, consider the case where the load is applied equally to right ribs 6 and 7. Since these are the loaded ribs in this scenario they are assigned a value of one for their normalized displacements (read from row L of Table 1), i.e., they will be equally displaced and displaced more than any of the remaining 18 ribs. The normalized displacements of right ribs 5 and 8 are read from rows S and I in Table 1 respectively, since right rib 5 is S with respect to rib 6 and right rib 8 is I with respect to rib 7. Therefore, the normalized displacements of right rib 5 and right rib 8, compared to ribs 6 and 7, are 0.84 and 0.44, respectively, shown in Table 2. Similarly, the normalized displacements for left ribs 6

Table 1. Normalized adjacent rib displacements.

Location	Rib 1	Rib 2	Rib 3	Rib 4	Rib 5	Rib 6	Rib 7	Rib 8	Rib 9	Rib 10
Superior (**S**)	X	0.46	0.53	0.72	0.74	0.84	0.82	0.74	0.42	0.42
Loaded (L)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Inferior (**I**)	0.79	0.38	0.61	0.70	0.67	1.0	0.44	0.52	0.77	X
Contralateral (**C**)	0.22	0.14	0.24	0.41	0.50	0.50	0.48	0.19	0.18	0.18

Table 2. Normalized ribcage displacements (load applied to right ribs 6 and 7).

Side	Rib 1	Rib 2	Rib 3	Rib 4	Rib 5	Rib 6	Rib 7	Rib 8	Rib 9	Rib 10
Right	(0.24)(0.46)	(0.45)(0.53)	(0.62)(0.72)	(0.84)(0.74)	0.84	1.0	1.0	0.44	(0.44)(0.52)	(0.23)(0.77)
	0.11	0.24	0.45	0.62	0.84	1.0	1.0	0.44	0.23	0.18
Left	(0.11)(0.22)	(0.24)(0.14)	(0.45)(0.24)	(0.60)(0.41)	(0.84)(0.50)	0.50	0.48	(0.44)(0.19)	(0.23)(0.18)	(0.18)(0.18)
	0.024	0.034	0.11	0.25	0.42	0.50	0.48	0.083	0.041	0.032

and 7 are read from row C in Table 1, i.e., 0.50 and 0.48, respectively, since these are the contralateral ribs. To obtain the normalized displacements of the other ribs, we assume that the ribs are coupled linearly. For example, when right rib 5 is displaced then left rib 5 will be displaced by 0.50 of the amount that right rib 5 is displaced since left rib 5 is contralateral (read from row C in Table 1) with respect to right rib 5. The normalized displacement of right rib 5 in Table 2 is 0.84 so the normalized displacement of left rib 5 will be (0.84)(0.50) = 0.42. Similarly, right rib 4 will be displaced by 0.74 of the amount that right rib 5 is displaced since right rib 4 is superior (read from row S in Table 1) with respect to right rib 5. The normalized displacement of right rib 5 in Table 2 is 0.84 so the normalized displacement of right rib 4 will be (0.84)(0.74) = 0.62. This process is continued until the normalized displacements for all 20 ribs have been calculated in Table 2. The normalized displacements listed in Table 2 are specific to a given scenario, i.e., they must be recalculated for each different scenario. However, the values in Table 1 never change as they represent the fundamental coupled mechanics of the thoracic cage.

To determine the total normalized displacement of the ribcage, the normalized displacements listed in Table 2 are summed. The proportion of the load applied to each rib is equal to the amount that it is displaced as its proportion of this sum. To calculate the absolute displacement of each rib, consider the thoracic cage as an array of parallel rib springs. Each rib spring is displaced by a fraction of the displacement of right ribs 6 and 7 based on the value listed in Table 2 for that rib. The load supported by each rib spring is equal to the stiffness of the rib multiplied by the absolute displacement of the rib, i.e., the spring force is equal to the spring stiffness multiplied by its displacement. Since the rib springs act in parallel, the sum of the loads supported by each rib spring is equal to the total load.

Stiffness of 95 isolated ribs was measured in three studies [2,4,5] from which we determined the mean rib stiffness to be 2.85 N/mm. Since there was no systematic variation in rib stiffness for different thoracic levels, a single value equal to the mean was assumed for all ribs. In the intact thoracic cage, muscles, connective tissue, skin and internal organs also contribute to the stiffness. Their contribution was estimated to increase the stiffness by a factor of 2.15, based on the mean of values reported in [5,6]. Therefore, each rib was characterized by a total stiffness of 5.96 N/mm.

Results

Table 2 was created for the specific scenario where the load is applied over right ribs 6 and 7. Suppose that an officer with a weight of 90 kg (883 N) kneels on the back of a suspect lying prone on the ground and places one knee over right ribs 6 and 7. The total normalized displacement (sum of the values for all 20 ribs in Table 2) is 6.86. Right ribs 6 and 7 each undergo one unit of normalized displacement which represents 14.6% (1/6.86) of the total normalized displacement. Since each rib in the thoracic cage supports a proportion of the total load equal to its proportion of the total normalized displacement, ribs 6 and 7 each support 14.6% of the total load. If the officer applies all of his weight, then (90)(0.146) = 13.1 kg (129 N) will be applied to each of right ribs 6 and 7. Given that each rib was

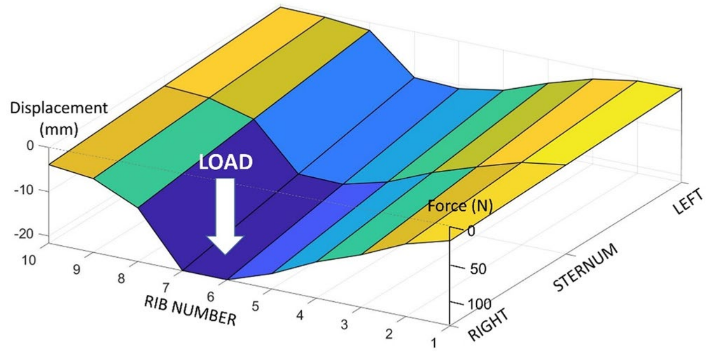

Figure 2. Absolute displacement and force distribution over the right and left ribs of the thoracic cage when a load is applied to right ribs 6 and 7.

modelled as a linear spring with a stiffness of 5.96 N/mm, the displacement of right ribs 6 and 7 would each be equal to the applied force divided by the stiffness, i.e., $129 \div 5.96 = 21.6$ mm. The absolute force and displacement of each rib for this specific scenario is shown graphically in Figure 2.

If the load had been distributed over more ribs, the loaded ribs would have experienced even less force and undergone less displacement. For example, consider a new scenario in which the officer's weight is applied over right ribs 5, 6, 7 and 8. In this case, right ribs 5, 6, 7 and 8 would all have values of one in Table 2 for this new scenario. The other ribs would generally have larger normalized displacements than those currently listed in Table 2, since they would be closer to the loaded ribs and, therefore, coupled more strongly to the loaded ribs. For example, right rib 4 would have a normalized displacement of 0.74 rather than 0.62. Consequently, the sum of the normalized displacements would be greater than 6.86 so one unit of normalized displacement would represent a smaller percentage of the total normalized displacement than 14.6%.

Discussion

Our model of the thoracic cage permits determination of both the load and the displacement of each rib. Without such a model it might be assumed that when an officer kneels on a suspect's back that 100% of his weight is applied to the ribs directly under his knee. In the above example, it would imply that 100% of the officer's weight is applied to right ribs 6 and 7. However, as the model shows, the force applied to right ribs 6 and 7 combined is only 258 N whereas the officer's weight is 883 N. The remainder of his weight is distributed among the other 18 ribs, all of which experience even less force and are displaced less than right ribs 6 and 7. In this example, not taking into account sharing of the load among all of the ribs would overestimate the force applied to right ribs 6 and 7 by a factor of 3.4. Such a large difference has significant implications for the risk of injury. Since force and displacement are proportional in the model, the displacement of ribs 6 and 7 would also have been overestimated by a factor of 3.4. A risk curve for rib fracture, based on rib displacement, was created from the data used to construct the thoracic cage model. For a displacement of 21.6 mm, the risk of fracture is less than 1% as opposed to 95% if the displacement was multiplied by a factor of 3.4. This marked difference in injury risk demonstrates the value of employing a computational model, based on a validated biomechanical structure, in the forensic investigation of injury.

Although the model assumes that each rib has the same stiffness, it would be possible to assign different stiffness values to different ribs. For example, a shorter or thicker rib could be given a higher stiffness than a longer or thinner rib. However, the model already takes this into account to some extent since the relative amount that adjacent ribs were displaced in the study used to create the model [3], was partly determined by their relative stiffness. Furthermore, the studies with isolated ribs did not identify any systematic differences in stiffness across ribs [2,4,5].

Although the load is constant in the scenario of the example, the model could be adapted for a scenario where the load is changing dynamically, for example during a punch or a kick. This would require the incorporation of soft tissue viscosity [7]. If the kinetic energy of the punch or the kick can be estimated, for example, from video evidence, the rib displacement could be determined from equations for energy transformation. The kinetic energy would be partially dissipated by the soft tissue damping and partially transformed into elastic energy stored in the ribs. The displacement of each rib equal to its stiffness multiplied by it displacement squared. In this way, the rib displacement and force could be estimated from which the risk of rib fracture could be determined.

The principal limitation of the model is that it assumes that the ribs act like linear springs. Although ribs do mimic linear springs over displacements of about 20 mm, their stiffness decreases somewhat for larger displacements. In addition, as indicated above, the tissue surrounding the ribs in the intact thoracic cage, dissipates energy and the model would have to incorporate soft tissue viscosity to take this into account in the case of dynamic forces [7]. However, energy dissipation is not a factor for a constant load when there is little motion. Furthermore, for many scenarios the rib displacements will not appreciably exceed 20 mm in which case the model parameters will not require modification. Larger displacements can still be accommodated by the model by simply reducing the stiffness. Appropriate stiffness values for larger displacement can be derived from results presented in some of the cited studies [3–5].

Conclusion

A model of thoracic cage has been presented and applied to a common use of force scenario. The value of the model is demonstrated in its ability to predict risk of rib injury. In particular, the risk of injury in the selected police arrest technique is shown to be much lower than would be expected from overly simplistic assumptions.

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