Translating Post-mortem Human Subject Injury Risk to Dummy Injury Risk at Iso-energy

Maria A. Ortiz-Paparoni, Concetta F. Morino, Joost Op 't Eynde, Jason R. Kait, Cameron R. Bass

Abstract Injury risk assessment based on post-mortem human subject (PMHS) data is essential for informing safety standards. The common *'matched-pair'* method, which matches energy-based inputs to translate human response to dummy, consistently results in less conservative human injury risk curves due to intrinsic differences between human and dummy. Generally, dummies are stiffer than PMHSs, so force and displacement cannot be matched simultaneously. Differences in fracture tolerance further influence the dummy risk curve to be less conservative. For example, translating a human lumbar injury risk curve to a dummy of equivalent stiffness using matched-pair resulted in a dummy injury risk over 80% greater than the PMHS at 50% fracture risk. This inevitable increase occurs because the dummy continues loading without fracture to attenuate energy beyond the '*matched*' PMHS input selected. Human injury response should be translated using an iso-energy approach, as strain energy is well associated with failure in biological tissues. Until PMHS failure, dummy force is related to PMHS force at iso-energy. Beyond PMHS failure, dummy force is related to PMHS force through failure energy. This method does not require perfect PMHS/dummy biofidelity and ensures that energy beyond PMHS failure does not influence the injury risk function.

Keywords injury risk reference, injury risk translation, iso-energy method, matched-pair testing, risk modelling

I. INTRODUCTION

Injury assessment references values (IARVs) and curves (IARCs) based on post-mortem human subject (PMHS) data are widely used in multiple applications such as the enhancement and development of occupant restraint systems, anthropometric test devices, airbag systems, policy regulation, and retrospective analysis of injuries in the field, among other applications [1-7]. These human injury assessments have directly informed performance requirements for dummy devices used in assessing injury risk for various loading scenarios[5],[8-11]. To develop IARCs, one widely used approach is *'matched-pair'* testing where both the ATD and PMHS are evaluated under similar loading, boundary and initial test conditions often with an energy-based input such as a mass impacting with a defined input velocity [12-16]. While this method seemingly provides a direct correlation between measured dummy response and PMHS outcome, solely relying on this approach depends on the capability of the dummy to largely mimic the human response and fracture behaviour under the corresponding loading and boundary conditions. While current dummy models may mimic human response to a certain degree, it is crucial that the dummy results are interpreted appropriately and interpreted only until PMHS failure energy. The objective of this study is to illustrate the inherent drawbacks of the matched-pair method and to propose that PMHS injury risk results should be translated to dummy injury risk using an energy-based approach

The degree of dummy biofidelity is limited by constraints and dummy design requirements; and matched-pair testing can result in an overestimation of the human injury point due to intrinsic differences in both material behaviour and performance to failure between the dummy and human. First, force and displacement generally cannot both be matched between PMHS and dummy since dummies are generally stiffer than PMHSs. Differences in stiffness result in unequal mechanical work done when either force or displacement is matched (Figure 1).

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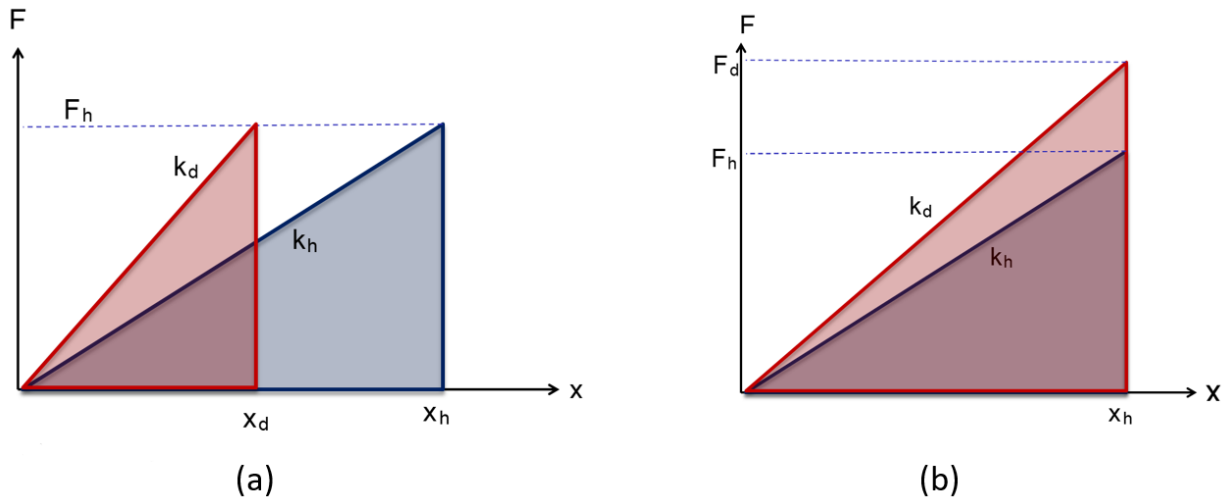

Fig. 1. (a) When matching for force between a dummy and human with different stiffnesses, the mechanical work (area under the curve) will not be equal. (b) The same consequence is true when matching for displacement with different stiffnesses.

While the stiffness difference between dummy and human is generally well understood, the crucial issue with matched-pair testing is a consequence of the robust dummy design. In injurious loading scenarios, when PMHSs fail, typically compromising load bearing capacity, the dummy is designed to remain intact. In the PMHS, tissue failure often limits the peak forces and moments. Using the matched-pair approach, energy-based inputs are matched and the dummy results from this matched input are interpreted to correspond to the PMHS at failure. For any given injurious input into the PMHS, the PMHS will fail at some energy and because this typically compromises the PMHS load bearing capacity, any energy input beyond failure does not influence the PMHS injury risk. However, because the dummy does not fail, any energy input beyond the threshold of energy that causes failure in the PMHS (Figure 2) will be incorporated into the dummy IARC. This inevitably results in unrepresentative risk metrics for surrogates, overestimating injury tolerance by an unknown extent based on arbitrarily selected input conditions. Unless a study is particularly concerned with mechanical behavior beyond failure, the injury translation from human to dummy should only incorporate the PMHS behavior up to failure. While it would be desirable to only test the dummy to this failure energy threshold, it is not possible to select these values *a priori*. The exact PMHS energy-to-failure is unknown prior to testing and will vary between the PMHSs.

Therefore, even assuming identical stiffnesses between PMHS and dummy, energy deposition in the dummy will produce higher peak forces in the dummy than the PMHS forces that are limited by failure at injuries, resulting in a much higher injury tolerance in the dummy surrogate. This leads to nonconservative human injury risk models. To properly compare results between PMHS and dummy, human injury response should be translated to a dummy IARC using an iso-energy method.

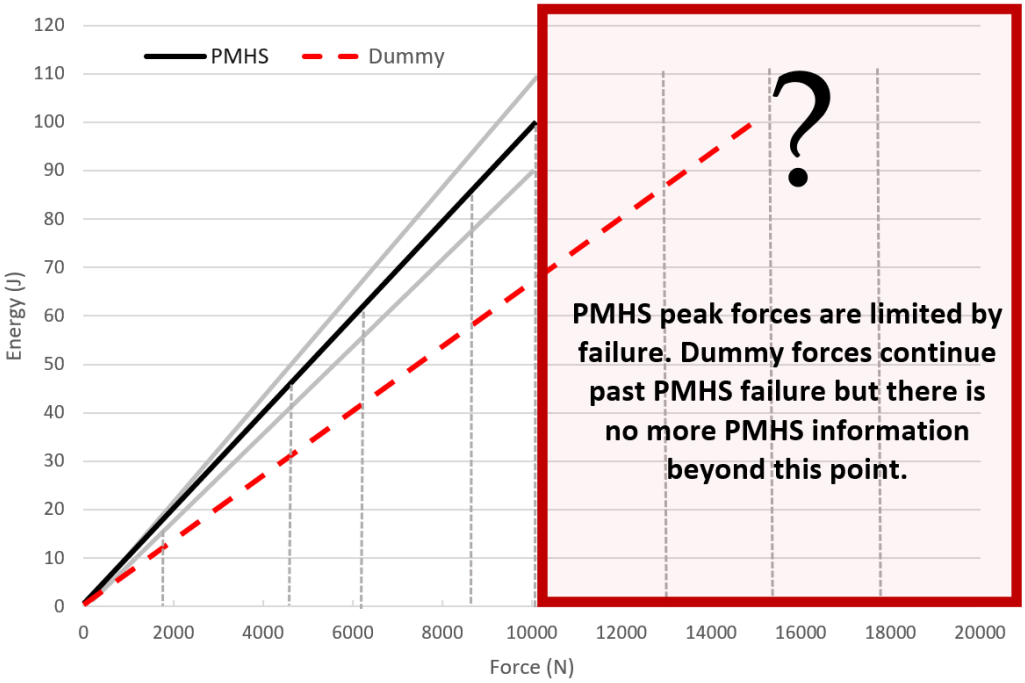

Fig. 2. Iso-force equivalency method on a generic linear elastic dataset for HIPC to IARC translation. Because the dummy has a much larger fracture tolerance, it will withstand forces beyond the PMHS failure point, yet there is no further PMHS force data to inform the dummy response.

II. METHODS

To ensure appropriate injury risk translation from human to dummy, the strain energy until failure is matched. Strain energy, an invariant scalar value, is well associated with failure in biological tissue [17-19]. Strain energy for a simple linear elastic model is defined in Equation 1 where F_X represents the inertially compensated load cell value (unaffected by acceleration), and dx represents the incremental displacement measured by the linear variable differential transformer, or LVDT. Rather than matching an energy-based input between the PMHS and dummy, the two responses are translated at iso-energy. Strain energy for a linear elastic model is shown here for simplicity. The energy calculation will depend on the specific loading configuration. It's important to note that in this example, moment is not contributing to the injury risk. While this energy equivalency method can be applied to more complex loading scenarios, a combined energy metric must be employed beyond purely axial loading.

$$E = \int F_X \cdot dx \tag{1}$$

For a simple linear elastic model:

$$F = kx \tag{2}$$

$$E = \frac{1}{2} F \cdot x = \frac{1}{2} k x^2 \tag{3}$$

Equating energy between human (h) and dummy (d):

$$E = \frac{1}{2} k_h x_h^2 = \frac{1}{2} k_d x_d^2 \tag{4}$$

To illustrate how the method is used, PMHS lumbar injury tests and a lumbar computational dummy model are shown for comparison in Figure 3. For more information on the development of the lumbar computational model, refer to [20]. The PMHS data comes from [21], where 13 full lumbar (T12-S1) specimens were tested under high-rate dynamic loading conditions. For more details on this PMHS test methodology, refer to Ortiz-Paparoni et al. 2021 [21]. The stiffness for this specific dummy computational lumbar injury model was not equivalent to the PMHS stiffness, as this is typically the case for dummy surrogates. PMHS lumbar components were subject to high-rate axial compression. The computational model was subject to the same loading conditions as the PMHS.

The average PMHS response was fit to a polynomial along with the standard deviation. Injury points were then translated from PMHS to dummy at each iso-energy level. Injury was defined as major vertebral body fracture. In this example, 20 J of energy corresponded to a PMHS force of nearly 4000 N and a dummy force of approximately 8500 N. Up until PMHS failure, dummy force can be related to PMHS force at iso-energy. Beyond PMHS failure, the dummy force is related to PMHS force at failure energy. Using this method, any energy input to the dummy beyond the PMHS failure point does not affect the development of the injury risk function.

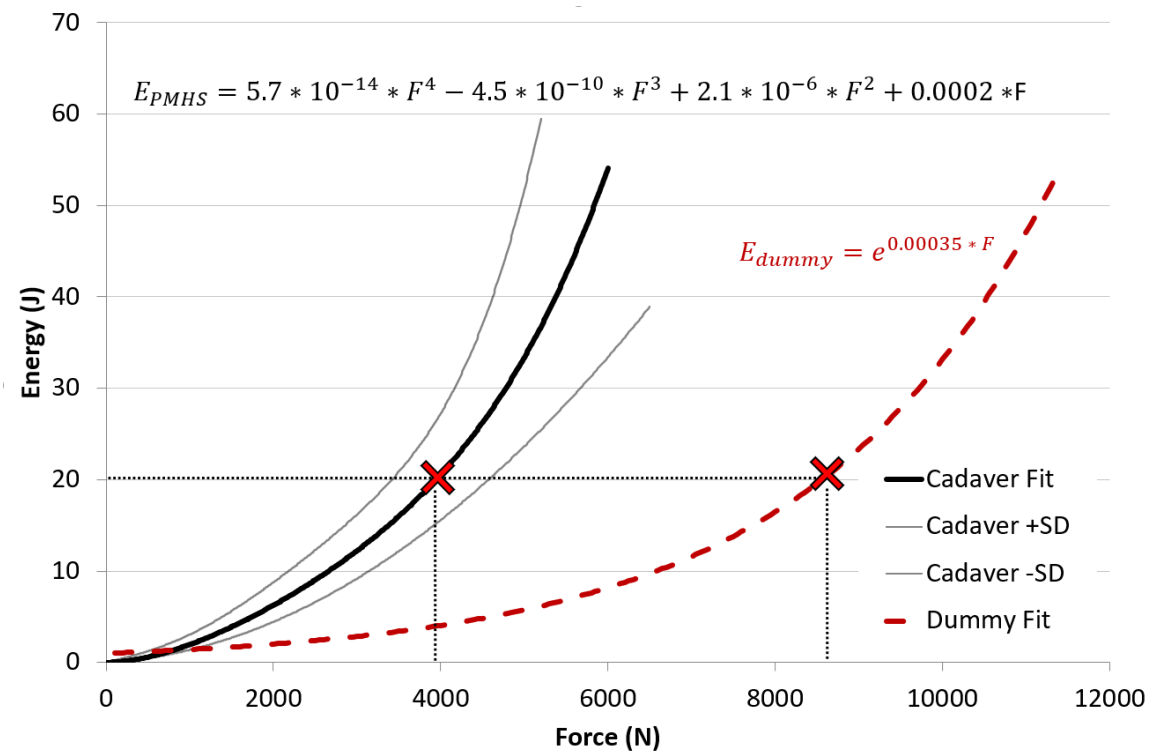

Fig. 3. PMHS force-energy response (solid back line), PMHS standard deviation (solid grey lines), and dummy force-energy response (red dashed line). PMHS and dummy response can be translated at iso-energy levels, illustrated here at the 20 J energy level.

When applying the proposed energy method in practice, it is likely that the dummy and PMHSs exhibit different stiffness properties. Therefore, the methodology presented above demonstrates how to apply this method for practical scenarios.

However, a major limitation of the matched-pair approach comes from the intentional design choice for the dummy to be robust with much higher failure tolerance than humans. To clearly and explicitly illustrate the difference between the matched-pair approach and the proposed energy method, a simple linear elastic computational model was created to have the exact stiffness properties of the PMHS. Further, the computational model was designed not to fail at the PMHS failure energy. Using these two simple PMHS and dummy models, injury risk was translated using both the proposed energy method and using matched-pair. The following section presents results using these two simplified PMHS and dummy models.

III. RESULTS

When using the matched-pair approach, any energy input into the dummy beyond the PMHS failure point will invariably increase the reference injury assessment to less-conservative values (Figure 4a). For equal stiffness, this change in the injury risk assessment can be dramatic. For this test series, the input nonfailure PMHS energy obtained in this test series averaged 35.05 ± 15.10 J while the mean failure energy at peak force was 94.19 ± 53.55 J. In a robust dummy model that does not break but has equivalent stiffness to the PMHS, the dummy matched-pair injury risk is shifted substantially to the right compared with the dummy-energy equivalence injury risk (Figure 4b). For the given dataset, at the 50% injury risk level, the matched-pair approach shifts injury risk to the right by nearly 4000 N, over 80% greater than the PMHS. Matching for energy to failure eliminates this injury tolerance overestimation, producing a dummy risk curve that lies directly on top of the PMHS risk curve under the equivalent stiffness assumptions.

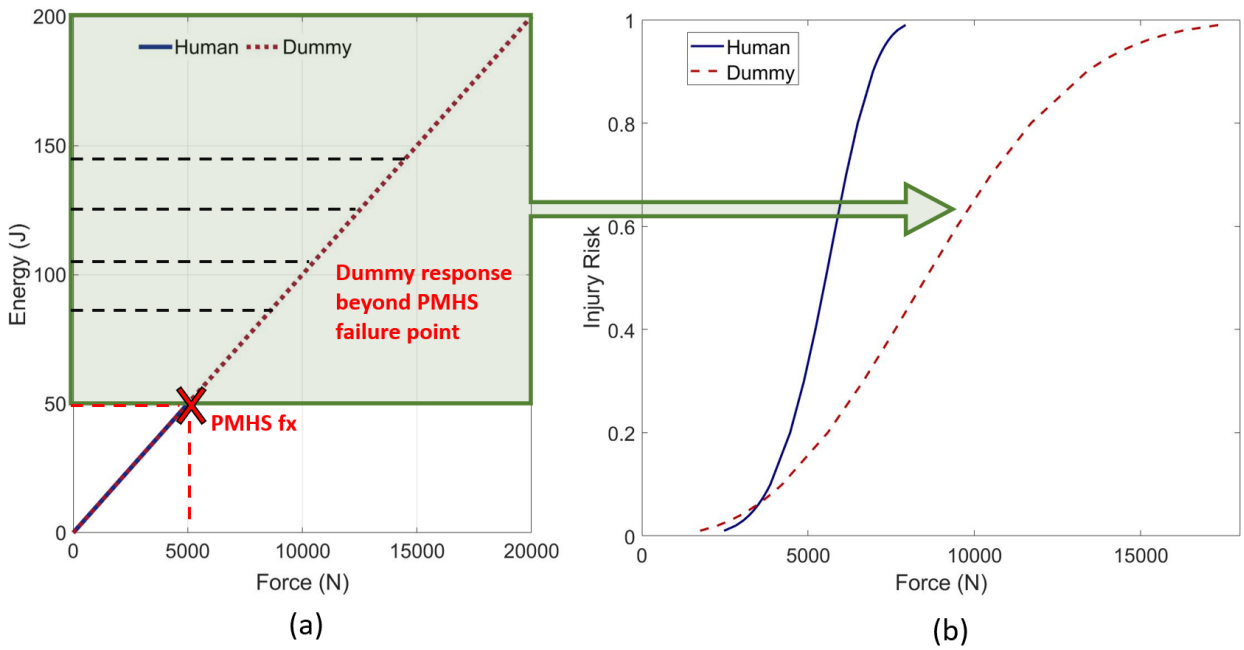

Fig. 4. (a) Shown on a simple linear elastic model, even when ensuring dummy and PMHS have equivalent stiffness, the dummy is often designed not to break. (b) Shown with real PMHS injury data and a dummy model designed with equivalent stiffness (blue solid line), any energy input to the system beyond the PMHS failure point, an inevitable consequence of the matched-pair approach, will result in a less conservative, higher injury tolerance for the dummy (red dashed line) when compared to the PMHS.

IV. Discussion

The commonly used matched-pair approach assumes nearly identical dummy and human responses under matched loading. Due to intrinsic differences in biofidelity and fracture tolerance, this method consistently overestimates injury tolerance, producing nonconservative safety standards informed by unrepresentative injury risk. It is important to note that it is not possible, *a priori*, to select input PMHS and dummy energies for matched-pair testing that exactly correspond to failure due to PMHS variation and the initially unknown injury values. This invariably results in dummy force values (and risk values above the mean fracture energy) that are larger than PMHS force values for a given failure energy/force. The iso-energy approach does not depend on complete biofidelity between human and surrogate. Most importantly, it avoids overestimating injury tolerance, an inherent drawback to the matched-pair approach.

Developing injury risk assessments is typically a complicated task as concerns over data censoring need to be discussed. This method takes no position on the type of censoring used in the development of the human injury risk. This iso-energy approach is strictly concerned about the translation of human injury risk to dummy, and not about developing the human injury risk. The concerns over data censoring, while important in the development of the human injury risk, do not contribute to the injury risk translation. Both censored and exact data can be translated using the proposed energy method. The main objective of this study is simply to highlight why differences between human and dummy properties create problems when applying the matched-pair approach to interpret dummy response and how translating risk of failure through iso-energy methods avoid these inherent matched-pair limitations.

It is worth noting that it can be difficult to determine energy directly given instrumentation limitations. In this methodology, energy is calculated from force and linear displacements for a purely axial system. In a system with both force and moment contributions, energy is determined from nonunique force/moment doublets and linear/angular displacement data. As the complexity of the system increases, determining energy becomes more difficult.

V. CONCLUSIONS

It is essential to ensure biofidelic risk translation from PMHS to dummy. The commonly used matched-pair approach consistently results in less conservative injury risk curves for humans due to differences in biofidelity between human and dummy including intrinsic stiffness and failure criterion. Because energy is well associated with failure in biological tissue, human injury response should be translated to dummy response using the iso-energy approach for appropriate injury risk translation. The matched-pair approach will invariably be nonconservative for the dummy under identical stiffness PMHS and dummy systems where the PMHS fails for the selected input conditions. However, the iso-energy translation method proves a translation from PMHS to dummy that produces the expected identical risk assessments when the dummy and PMHS have equal stiffnesses but different failure characteristics. While directly determining energy can be difficult, the appropriate way to translate injury risk from PMHS to dummy is through energy equivalence to avoid overestimating human injury tolerance.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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ERRATUM

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The author list was incorrectly reported in the first version of the manuscript: the second to last author should appear as “Roger W. Nightingale”. Please see above for the correct list of authors.