Reference Analytic Morphomics Population (RAMP): A Reference to Measure Occupant Variability for Crash Injury Analysis.

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Abstract Real world crash injuries occur to a large and highly variable population. Analytic Morphomics measures very detailed geometry and material characteristics for tissues, organs, and bones throughout the body using automated processing of medical imaging scans. We analyzed 416 occupants involved in motor vehicle crashes with full crash investigation as well as medical imaging scans and found that morphomic data improved risk stratification for thoracic 3+ injury in both frontal and side impact crashes. We then sought to define the population distribution of the morphomic factors identified to be significantly predictive of crash injury risk to the thorax. Chest, abdomen, and pelvis CT scans were collected from 5,268 patients, aged 16 to 91 years, at the University of Michigan, who were scanned primarily for trauma indications. This curated population, named the Adult Reference Analytic Morphomics Population (RAMP), is representative of typical vehicle occupants in the United States. Customized software was used to perform automated processing of these CT scans and to store detailed body geometry and composition data in an anatomically-indexed format. Quantile regression was performed to generate curves of morphomic factors corresponding to the 5th, 25th, 50th, 75th, and 95th percentiles from ages 16-91 for both men and women respectively. This is a very detailed body composition study based on a large cohort of people.

Keywords body composition, morphomics, population variability, RAMP

I. INTRODUCTION

Real world occupant crash injuries are the result of living tissues failing locally at sites where concentrated physical forces generated during the interaction of that occupant with a vehicle's interior structure and restraint systems exceed the ability of the tissues at that given site to tolerate the forces generated. Therefore, occupant factors such as the geometry and dimensions of the tissues being loaded as well as material properties of those tissues such as failure tolerance and force deflection characteristics are important in determining whether and where tissues fail in order to result in clinical injury [1].

The automotive industry has historically used vehicle and demographic data to guide their safety designs. The safety systems currently in place in the vehicle fleet have been developed with the use of anthropomorphic test devices (ATDs) that are idealized representations of the population. No single ATD can completely represent the myriad of fat or skinny, tall or short, young or old, healthy or unhealthy, muscular or deconditioned individuals that comprise its target population. Furthermore, the age distribution and physical characteristics of the general population have changed in the time since the targets for ATD development were originally chosen, making ATDs less representative of their target demographic in the current population [2]. Emerging trends in our crash injury database show that occupants with atypical body habitus are not benefiting as fully as those with "ideal" body habitus, from recent safety systems tuned to optimally protect ATDs in standardized crash tests [3-5].

In an earlier investigation of the factors that were most predictive of abdominal injuries [6], 18 covariate variables were examined (4 vehicle, 4 demographic, and 10 morphomic, derived from CT scans). Over 260,000 regression models were fitted using all possible variable combinations and ranked the models using Akaike

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Information Criteria (AIC) and a model-averaging approach to control for over-fitting in order to select the optimal predictive model. That study found that the models' performance had an area under the curve (AUC) of 0.646 for vehicle data only, 0.696 with vehicle plus demographic data, 0.866 with vehicle plus morphomic data, and 0.879 for the full model using vehicle, demographic, and morphomic data [6]. These findings support that morphomic variables are highly significant in the prediction of injury risk in live human subjects involved in real-world vehicle crashes.

In another prior study, we found multiple morphomic variables that might be of value in the development of human chest mathematical models used to assess occupant response and restraint performance [7]. Morphomic data are tangible measurements obtained from imaging files. The data characterize an individual's 3-dimensional anatomy and thus better represent the diversity of occupant size, shape, and condition. Demographic data cannot directly be accounted for in a human body finite element model or crash test dummy design, but morphomics data can [8]. Many numerical models, for instance cervical spine models, have been developed with an initial focus on the 50th percentile male [9] with input parameters based on analysis of small samples of CT scan measurements [10]. However, we have recently reported that neck morphomic features vary substantially with age and gender [11].

Detailed morphomics data, such as body geometry, fat distribution, and bone density gathered from large populations can be precisely adjusted in the models to represent occupants of different ages or body shapes and sizes and are thus valuable in assessing injury risk during vehicle crashes [12]. Advanced restraint technologies are becoming more common in the current vehicle fleet. The energy absorption properties in these restraint systems can be varied depending on the crash severity, occupant location, and size. The information obtained from morphomic data could eventually be used to further optimize the restraint system for each individual occupant.

Occupants of vehicles involved in motor vehicle crashes vary substantially in body stature, shape, and condition. For instance, two people can be 165 cm tall and weigh 79 kg, but if they are a 75-year-old woman and a 17-year-old man the differences between their muscle quality and fat distribution can be enormous. This variability contributes substantially to differences in injury severity and patterns in the real world [13]. Demographic factors such as age, gender, height, and weight are insufficient to describe human variability. Using morphomics, we previously measured variability using a large population of males similar in height and weight to the standards set for a 50th percentile American male (AM50) [3]. However, the current population is substantially different than when the AM50 standards were chosen multiple decades ago. For instance, obesity has become a worldwide epidemic, (cite, e.g. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2833287/) which can be captured through analytic morphomics at a granular level. In our current effort, we have attempted to define morphomic variability for both genders in a contemporary population of 5,268 adults.

II. METHODS

Crash Injury Analysis

The crash data was obtained from the International Center for Automotive Medicine (ICAM) for calendar years 1996-2015. ICAM was a part of the Crash Injury Research and Engineering Network (CIREN) from 1996 to 2010 and followed CIREN inclusion criteria. Since that time, ICAM has expanded its criteria to include anyone injured in a motor vehicle crash and transported to the University of Michigan, regardless of the severity of their injuries. Most of the vehicles were towed from the scene due to damage. Each crash was investigated and reconstructed. The crash data collected in the ICAM database is based on examining crash site and the vehicles involved using standard National Automotive Sampling System (NASS) protocols [14]. The data come from crash investigator reports, paramedic and medical records, police reports, and interviews. The vehicle data includes:

- Crash Severity: Change in vehicle velocity (delta V); miles per hour
- Total Longitudinal Intrusion: The sum of longitudinal intrusions (across the lower, mid, and upper instrument panel areas); centimeters
- Total Lateral Intrusion: The sum of lateral intrusions (across the lower, mid, and upper door or side panel areas); centimeters

- Belt use: Belt use or misuse was determined by the crash investigators. Designations included "3-Point Belt", "Shoulder Belt Only", or "Lap Belt Only".

RAMP Study Population

This study was approved by the University of Michigan Institutional Review Board (HUM00041441 and HUM00043599). Chest, abdomen, and pelvis CT scans were collected retrospectively from 5,268 patients, aged 16-91 years at the University of Michigan, who were scanned for trauma indications, between 04/1998 and 05/2015. Patient characteristics including age and gender were obtained from each CT scan. This population was named the Reference Analytic Morphomics Population (RAMP) version 0.0.4.

Analytic Morphomics

Analytic Morphomics processing was performed between 2012 and 2015 according to methods previously well described [15-17]. All scans (current crash analysis population and RAMP) were processed semi-automatically utilizing high-throughput image processing algorithms written in MATLAB 2015a (The MathWorks Inc., Natick, Massachusetts, USA). In brief, we first establish a common coordinate reference system for each scan by identifying individual vertebral levels. Then we identify the skin and fascial envelopes. Subcutaneous and visceral adiposity, pelvis, psoas and dorsal muscle group, as well as spinal trabecular and cortical bone density measurements are then performed at each vertebra level. Analytic Morphomic measurements are computed from the resulting body composition map. Multiple morphomic variables at each vertebral level were analyzed; those representative of the overall thoracic crash injury analysis results are presented below, including:

- Anterior vertebral body to fascia at L5 (VB2Fascia L5): Distance from the anterior aspect of the vertebral body out to the fascia at the medial body plane (linea alba)
- Dorsal Muscle Group (DMG) Ratio of low density to high density muscle at T10 (dmgldm_to_ndmarea T10): The cross sectional area of the DMG falling in a low density muscle HU range (0 to 30 HU), to Normal Density Muscle Area, the cross sectional area of the DMG falling in a normal density muscle HU range (31 to 100)
- Trabecular bone mineral density (HU) at T10 (bmdhuvbaligned T10): Average pixel intensity inside a mid-vertebral core sample
- DMG normal density mean (HU) at T11 (dmgndmmeanhu T11): Mean pixel intensity within Normal Density Muscle (31 to 100 HU) pixels inside the DMG boundary

These four parameters were chosen as they were most likely to be included in the majority of the total body CT that are done as the standard of care at the University of Michigan.

Statistics

Crash Analysis: Due to differences in the extent of body scanned as well as scanning artifact from positioning and scatter from metal, not all morphomic measures were available for every RAMP subject. 416 Crash occupants with full crash investigations and medical imaging scans were divided into two groups based on un-to-moderately injured occupants ($MAIS_{thx}$ 0-2) and seriously-to-critically injured occupants ($MAIS_{thx}$ 3+). Only injuries to the thorax were analyzed. Statistical analysis was performed using R version 3.2.3 [18].

RAMP: Quantile regression utilizing B-splines with different L1 penalty was performed to examine the non-linear relationship between patient age and various analytic morphomics measures, stratified by gender. For each measure, non-crossing quantile curves corresponding to the 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th} percentiles were estimated separately for males and females. The resulting curves were truncated at age 85 due to low sample sizes above age 86. All statistical analysis was performed using R version 3.2.3. Quantile regression analysis was performed using the R package 'quantregGrowth' [19].

III. RESULTS

TABLE I
COMPARISON OF MORPHOMIC, DEMOGRAPHIC AND CRASH VARIABLES
IN PATIENTS WITH AND WITHOUT $AIS_{THX}3+$ IN FRONTAL CRASHES

Morphomics & Crash Measure	$MAIS_{thx} < 3$ (n=160)	$MAIS_{thx}$ 3+ (n=119)	P-value
Age	43.6	53.0	<.001***
Gender (% Female)	56.6	49.2	.279
Height	170.0	172.2	.107
Weight	82.7	89.2	.035*
BMI	28.5	30.0	.144
Intrusion (Longitudinal)	25.9	26.7	.841
Intrusion (Lateral)	6.1	6.0	.946
Delta V (mph)	27.0	29.0	.161
Belt used (%)	75.8	76.3	1.000
VB2Fascia (mm) L5	92.3	106.1	<.001***
Ratio of low density (HU) to high density muscle Dorsal Muscle Group at T10	.255	.345	.001***
Bone mineral density (HU) T10	227.0	205.2	.002**
Dorsal Muscle Group density (HU) T11	61.3	59.3	.004**

TABLE II
COMPARISON OF MORPHOMIC, DEMOGRAPHIC AND CRASH VARIABLES
IN PATIENTS WITH AND WITHOUT $AIS_{THX}3+$ IN SIDE IMPACT CRASHES.

Morphomics & Crash Measure	$MAIS_{thx} < 3$ (n=60)	$MAIS_{thx}$ 3+ (n=77)	P-value
Age	34.0	42.6	.012*
Gender (% Female)	60.7	55.7	.606
Height	170.6	171.4	.612
Weight	76.1	78.8	.386
BMI	26.1	26.7	.534
Intrusion (Longitudinal)	5.3	6.1	.707
Intrusion (Lateral)	36.5	47.3	.077
Delta V (mph)	21.1	23.3	.145
Belt used (%)	72.1	80.5	.311
VB2Fascia (mm) L5	85.1	95.3	.036*
Ratio of low density (HU) to high density muscle Dorsal Muscle Group at T10	.156	.290	.001***
Bone mineral density (HU) T10	247.7	226.1	.040*
Dorsal Muscle Group density (HU) T11	65.3	61.2	<.001***

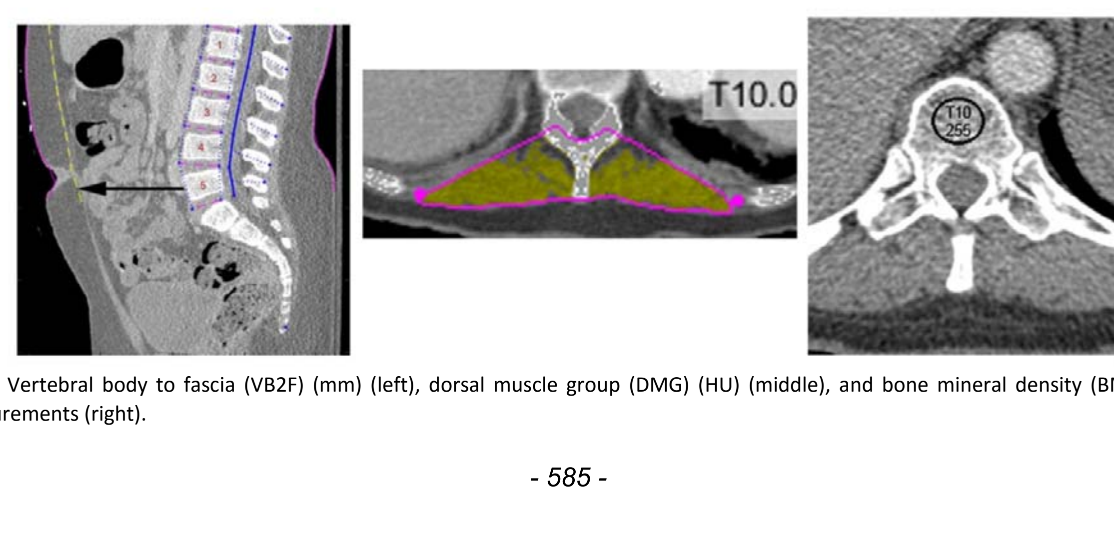


Fig. 1. Vertebral body to fascia (VB2F) (mm) (left), dorsal muscle group (DMG) (HU) (middle), and bone mineral density (BMD) (HU) measurements (right).

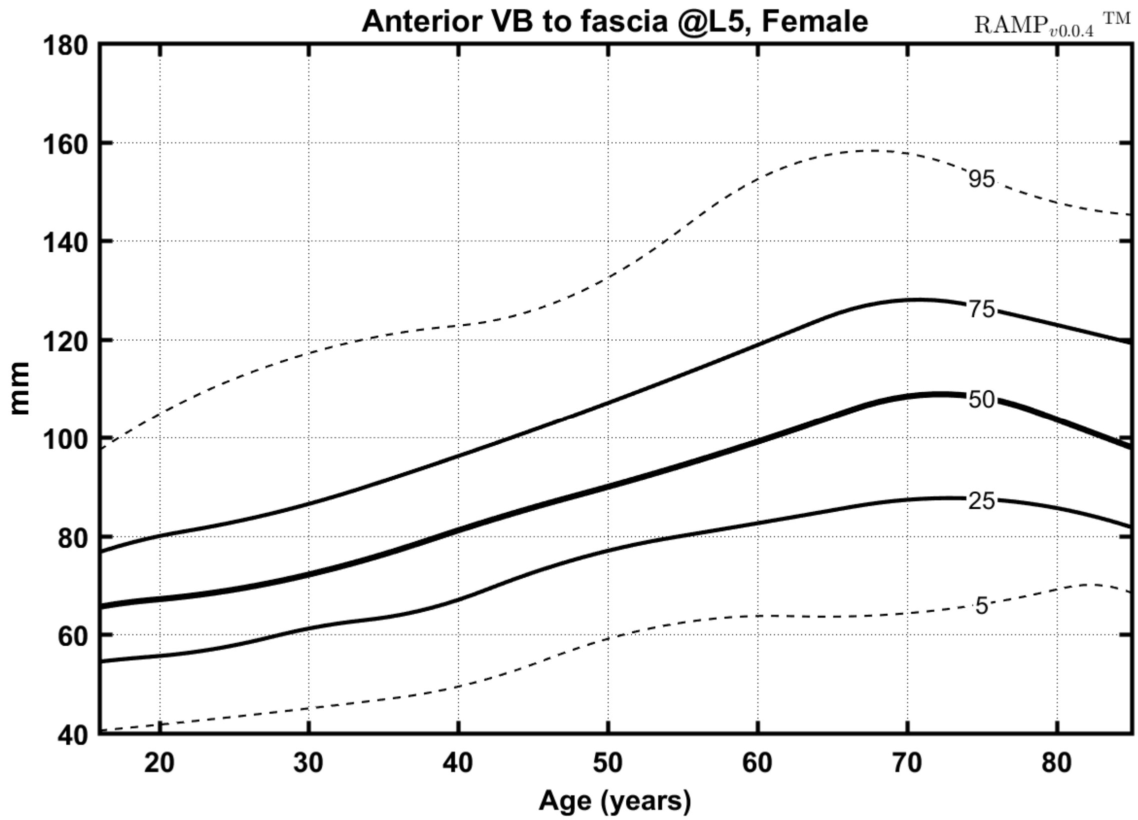


Fig. 2A. VB2Fascia (mm) L5 Female n=1,545

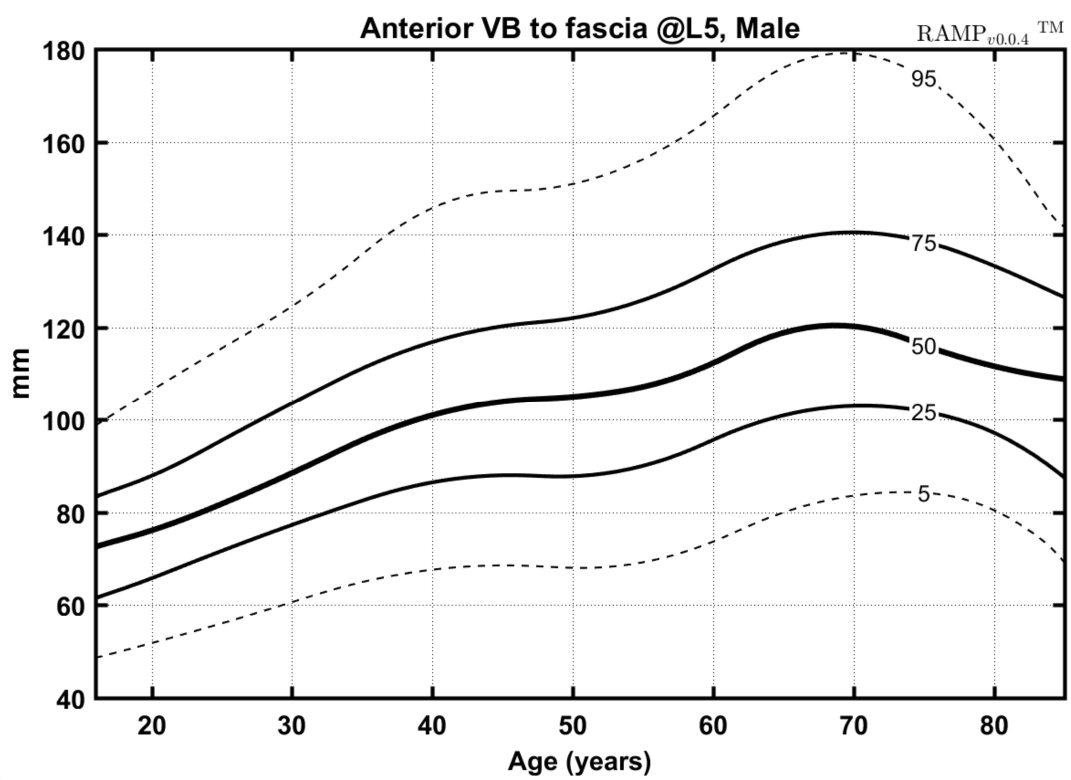


Fig. 2B. VB2Fascia (mm) L5 Male n=2,834

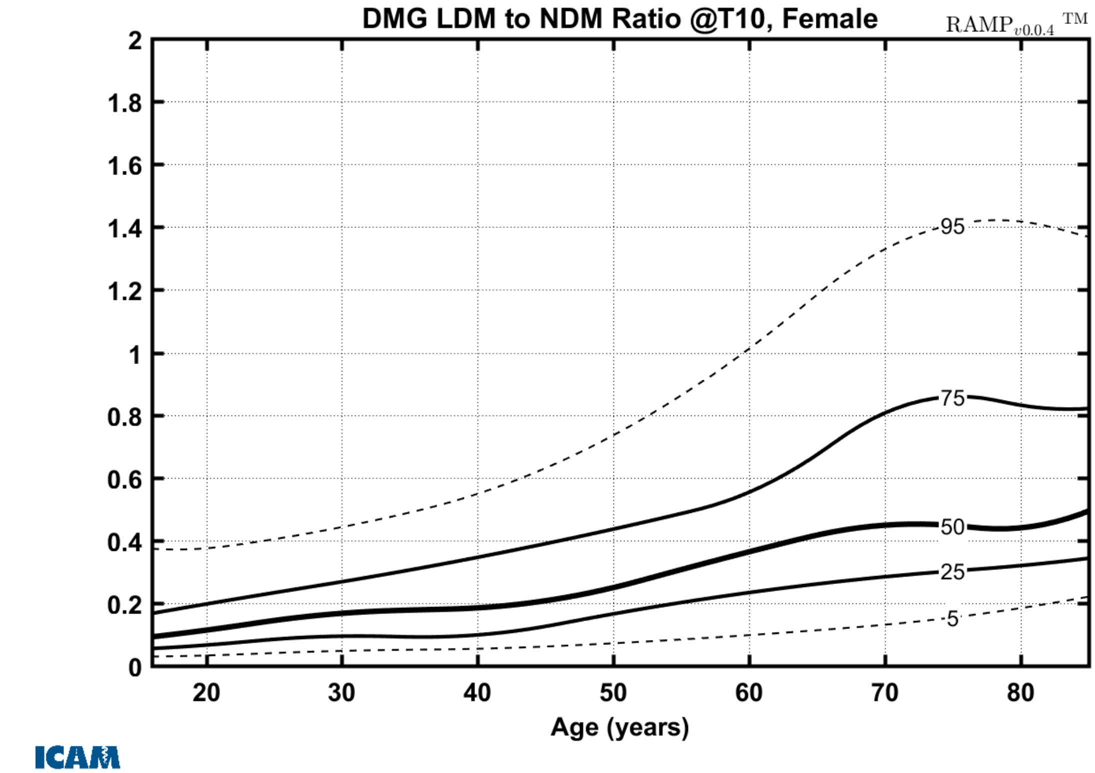


Fig. 3A. Ratio of low density to high density muscle in the Dorsal Muscle Group (HU) at T10. Female n=1,079

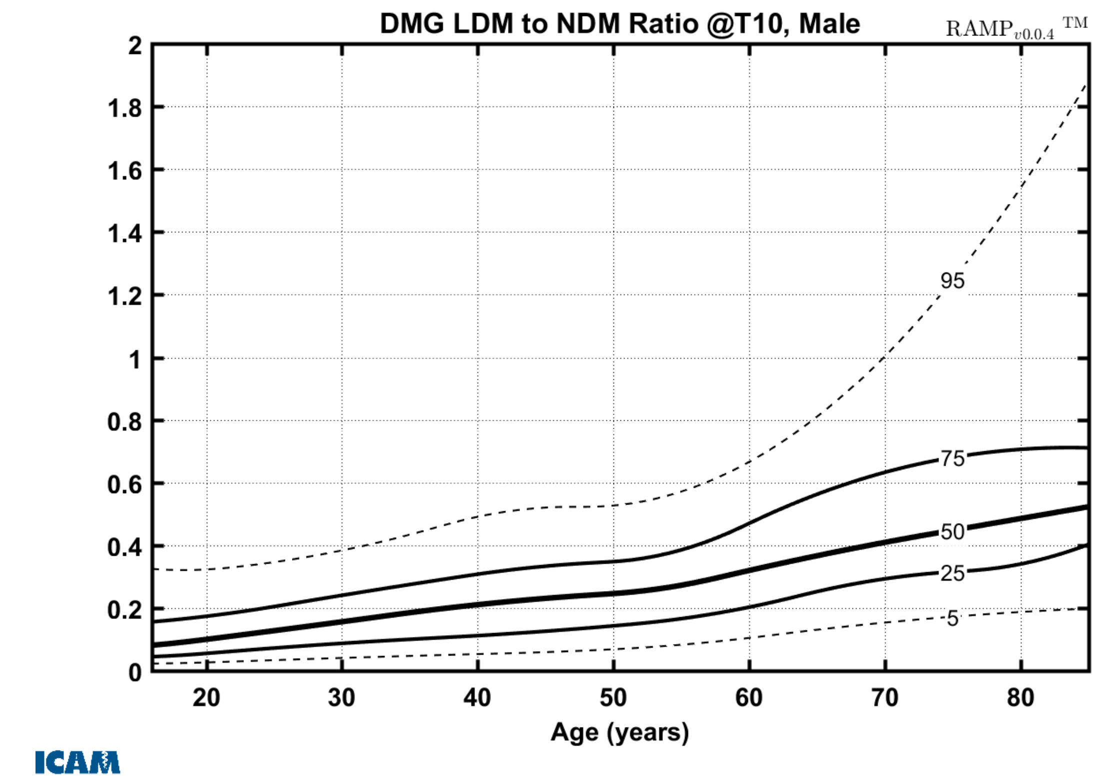


Fig. 3B. VB2 Ratio of low density to high density muscle in the Dorsal Muscle Group (HU) at T10. Male n=2,072

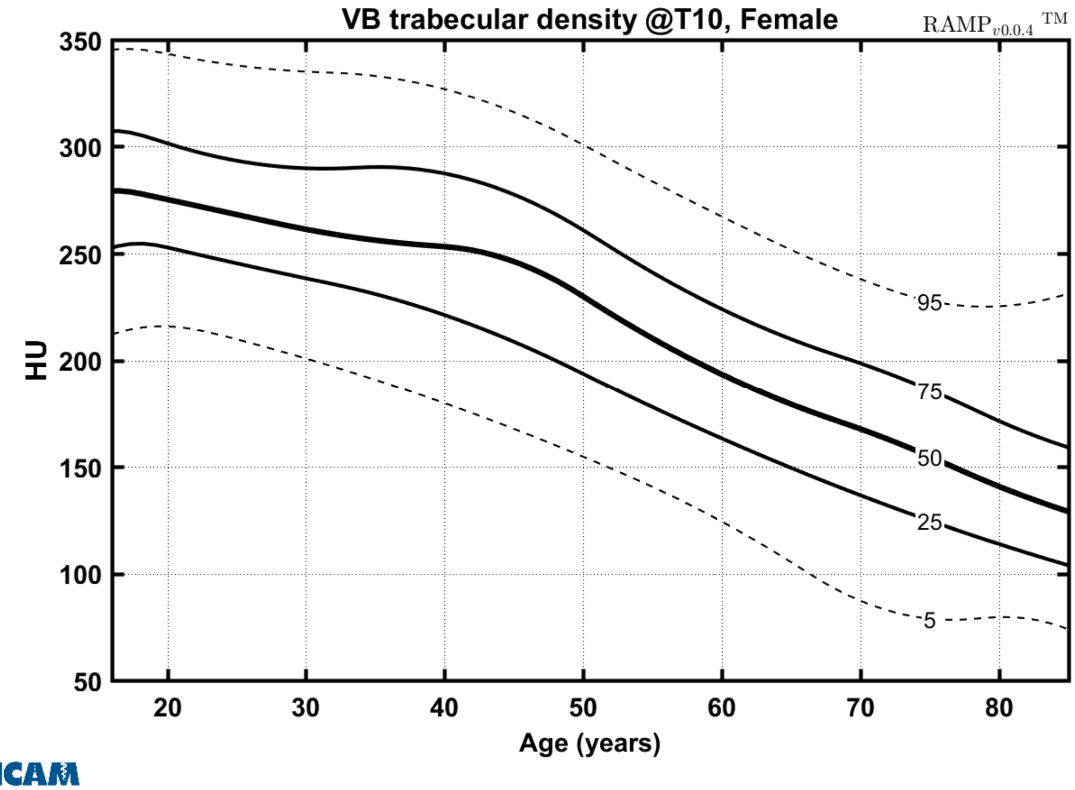


Fig. 4A. Bone mineral density (average HU) at T10. Female n=1,680

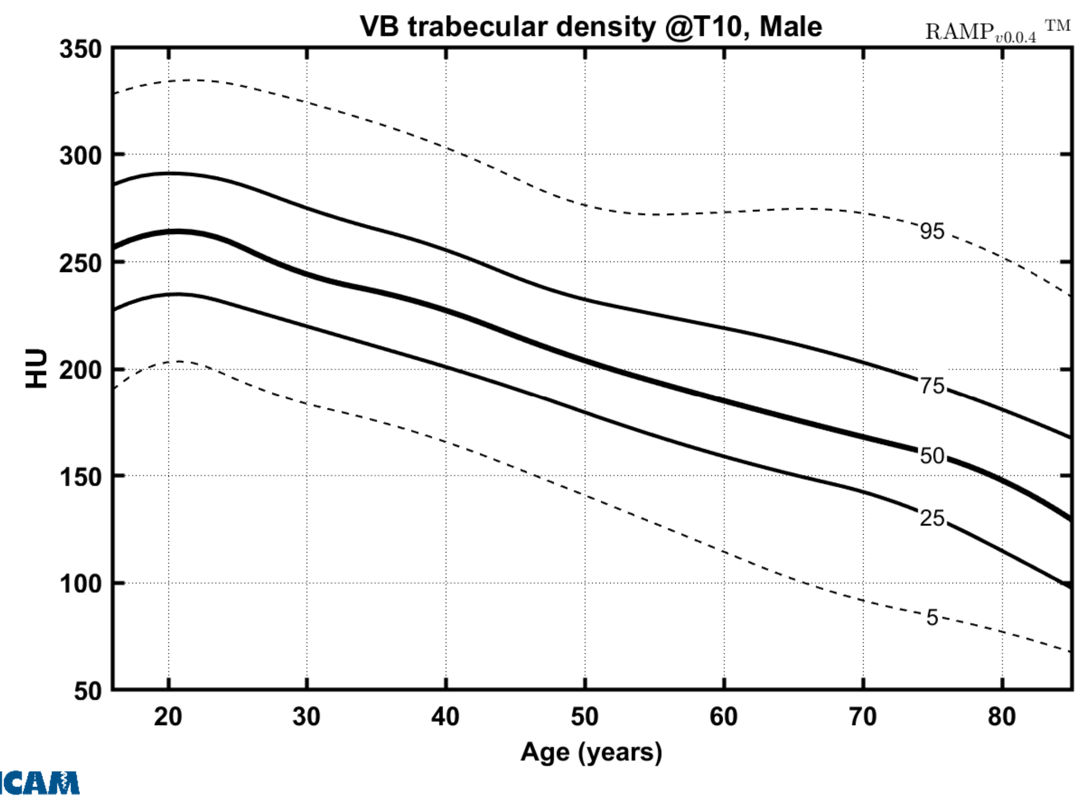
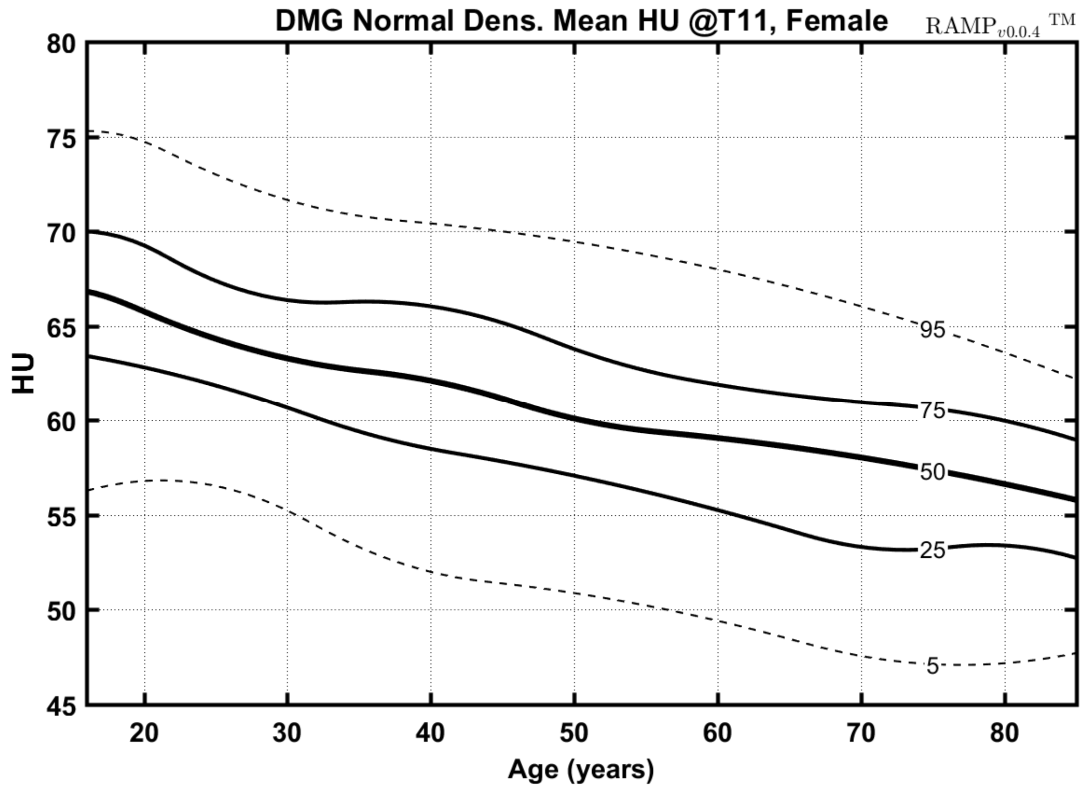
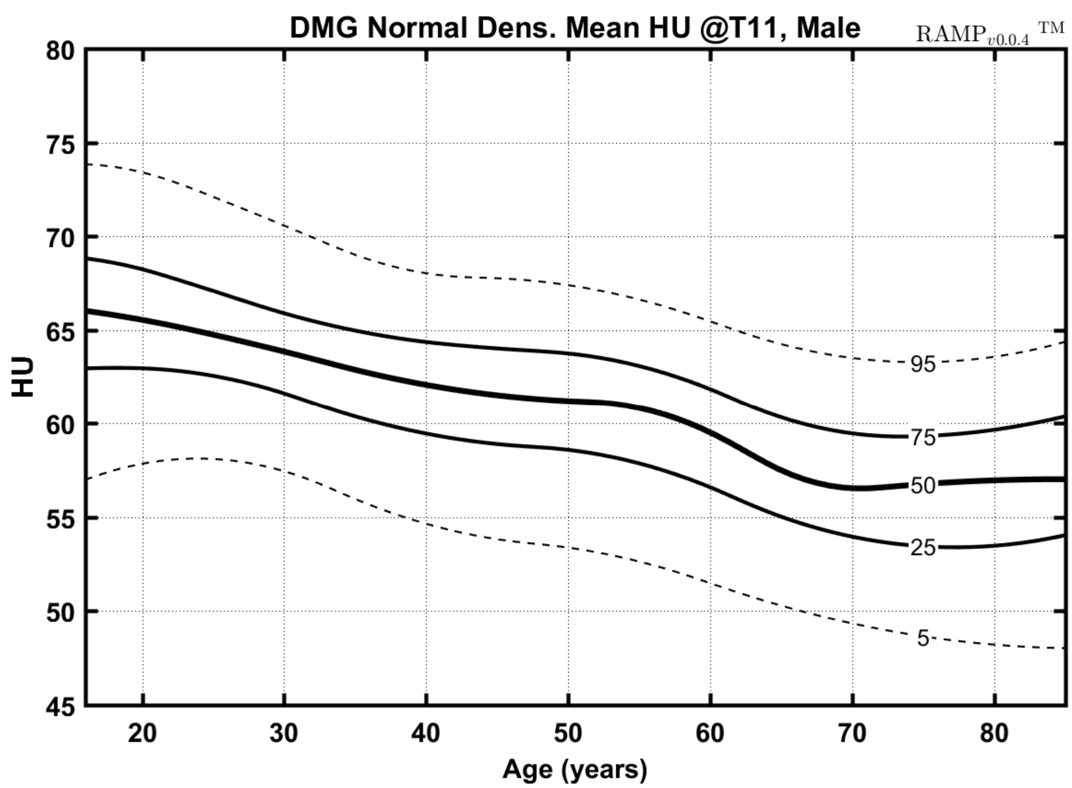


Fig. 4B. Bone mineral density (average HU) at T10. Male n=3,073



ICAM

Fig. 5A. Muscle density in Dorsal Muscle Group (HU) at T11. Female n=1,137



ICAM

Fig. 5B. Muscle density in Dorsal Muscle Group (HU) at T11. Male n=2,128

IV. DISCUSSION

Comparison of morphomic, demographic, and crash variables using univariate analysis (Tables 1 and 2) demonstrates several trends. Morphomic variables are more predictive of chest injury than vehicle factors. Aside from occupant age, the morphomic variables are more predictive of chest injury than the demographic variables. In both frontal and side impact crashes, a deeper visceral cavity at L5 is associated with more severe injury. While a deeper visceral cavity is positively correlated with increased BMI, visceral cavity depth is more predictive of chest injury severity than BMI. Decreased bone mineral density and decreased muscle density are both highly predictive of increased chest injury, consistent with previous findings that soft tissues, particularly muscles, contribute substantially to thoracic injury tolerance [20,21]. The decrease in muscle density is not a generalized decrease but rather an increase in the proportion of muscle fibers that are lower in density, consistent with increased fatty degeneration of muscle fibers that has been reported with aging.

The RAMP charts for the four morphomic variables show that there are substantial differences between genders and also with aging within each gender. The substantial differences between the 5th percentile, 50th percentile and 95th percentile curves highlight the substantial variability that exists within a contemporary population.

This study, using a large real-world crash occupant population as well as a very large reference population demonstrate not only the importance of morphomic factors in whether chest injuries occur but also the substantial variability for each of those morphomic factors within the current population. The Reference Analytic Morphomic Population (RAMP) is by far the largest population ever studied in such detail. Such data can be used to inform the design of future restraint systems as well as human body finite element models and anthropomorphic test devices. By looking at the pattern morphomic factors (dimensional vs geometric vs tissue property) that are most predictive of increased injury risk or injury tolerance in frontal versus side impact crashes, it is possible to generate hypotheses of injury causation that can be tested in the laboratory.

Study limitations

The ICAM database includes patients treated at a Level 1 trauma center and is therefore biased toward injured occupants. It is not representative of a national sample or occupant exposure. The database was not designed to assess injury rates. However it is unique since it contains detailed information on vehicle, demographic, and morphomic variables. These variables can be used in statistical models to identify which are most significant in predicting injury. Morphomic measurements were taken in supine position. The effect of individual patient posture or torso rotation was not controlled during scanning. HU measurements have been shown to depend on scan energy [22] and resolution [23]. While energy exposure and scan resolution may vary from one patient to another, these effects were not assessed in this study. However, clinical radiology protocols, such as daily calibration of CT scanners with phantoms, help to ensure consistency between patients.

V. CONCLUSIONS

Occupants of vehicles involved in motor vehicle crashes vary substantially in body stature, shape, and condition. This variability contributes substantially to differences in injury severity and patterns in the real world. Demographic factors such as age, gender, height, and weight are insufficient to describe human variability. The International Center for Automotive Medicine had analyzed a large curated Reference Analytic Morphomics Population (RAMP) that is representative of typical vehicle occupants in the United States. The distribution of morphomic variables within this population will inform and standardize the development of physical and virtual crash test devices and metrics.

These data are being published and made available via the Web to support vehicle safety efforts worldwide.

The data and calculator are available at:

http://www.med.umich.edu/surgery/morphomics/ramp

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