Manikin Design: A Case Study of Formula SAE Design Competition

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Digital Human Models (DHMs) are a tool used to aid the creation of products and objects designed with the end user in mind. Their use is particularly prevalent in the automotive industry. They can assist the designer in visualizing several elements of accommodation including fit and field of view. A potential related application is student vehicular design competitions. For example, SAE International hosts the Formula SAE series where the rules for the competition state that the vehicle must fit the dimensions of the "95th percentile US male". Unfortunately, many students involved in this event do not have a good understanding of human factors and ergonomics. The objective of this work was to create a set of DHMs that meet the requirements as outlined in the Formula SAE rulebook. A primer describing their use was also developed. Since Formula SAE is considering the inclusion of a requirement that a "5th percentile female" also fit in the cockpit of the vehicle, models based off of these dimensions were also creative. In addition to providing the models in the native DHM format, the models are available in several more accessible formats including VRML, PNG, and the JT open CAD standard.

Practitioner Summary: This work describes the creation of two digital human models for use in SAE International student design competitions. Primers describing their use were also created. They are available in a number of formats and should aid students with little training in ergonomics in human factors as they conduct their required assessments of fit.

Keywords: digital human models, vehicle design, SAE, student competitions

1. Objectives

Digital Human Models, or DHMs, are a valuable tool that assists designers by allowing them to assess user fit and other elements in the early stages of design. Evaluating fit with respect to body size and shape is important considering the variability within a population (e.g., 5th percentile female by stature compared to 95th percentile male by stature). This consideration is also important early in the design process to allow a design to be analyzed for how effectively and efficiently humans will be able to interact with it (Chaffin 2001). While these benefits are useful in industry, they are also appropriate in collegiate land vehicle design competitions.

SAE International hosts the Formula SAE (FSAE) series, design competitions that provide an opportunity for students to gain hands-on experiences through the design of prototype Formula style open wheel racing cars. In 2013, more than 2,000 students from over 200 university teams competed in North America alone (SAE 2014). This type of competition is growing and becoming more international with current competitions taking place in North America, Australia/Asia Pacific (Australasia), Brazil, Italy, the UK, Austria, Germany, and Japan. The competitions are also expanding to different types of vehicles including baja, snowmobiles, and hybrids.

In the design requirements for the FSAE series, students are directed to fit their design to the 95th percentile US male by height. If their design does not meet this requirement, the car will not be allowed to compete in the dynamic events within the competition. Unfortunately, most of the students involved in this activity have little experience in Human Factors and Ergonomics. To mitigate this shortfall and to take advantage of a learning opportunity associated with the event, a set of DHMs that meet the requirements as outlined in the FSAE rulebook were created (SAE International 2014). A primer describing their use was also developed. These materials will be made available online and will be freely accessible to students participating in this competition.

2. Selection of the Manikins

Through a collaboration with Siemens, a development version of the Jack human modeling system was used to create DHMs representing the US civilian population (Haupt 2014). From this set of models, the closest multivariate match to that recommended by SAE in section T3.10.4 in the FSAE rulebook (a 95th percentile male by stature) was chosen. Since FSAE is considering the inclusion of a requirement that a 5th percentile female also fit in the cockpit of the car, models based off of these dimensions were also selected.

Since there are many combinations of body measures that will comprise an individual of a given stature (Haslegrave 1986), several manikins exhibiting different shapes were selected (Fromuth and Parkinson 2008). The sub-population of manikins consists of three male manikins statures closest to 95th percentile and three female manikins with statures closest to the 5th percentile. The male manikins will be referred to as MM1 through MM3 and the female manikins will be referred to as FM1 through FM3. The dimensions used to create these manikins can be found in Table 1.

Table 1. Dimensions of 95th percentile males and 5th percentile females from database in mm.

	Male			Female		
	MM1	MM2	MM3	FM1	FM2	FM3
Stature	1883	1883	1883	1507	1507	1506
BMI	29	30.7	36.2	22	25	39.3
Sitting Height	991	965	983	816	802	818
Biacromial Breadth	452	437	436	346	372	401
Sitting Knee Height	610	608	609	476	466	486
Forearm-Hand Length	522	522	519	418	419	419
Hip Breadth Sitting	425	398	471	359	390	474
Head Circumference	576	629	609	565	537	566
Chest Circumference	1097	1173	1246	855	890	1214
Waist Circumference	934	1076	1181	719	757	1097
Buttock Circumference	1125	1056	1281	897	1018	1239

3. Building the Posture

The main resource for creating the posture was rule T3.10.4 from the 2015 FSAE rulebook, seen in Figure 1. This template outlines the positioning of the 95th percentile male within the vehicle. The template is accompanied by the following text (SAE International 2014):

a) The seat will be adjusted to the rearmost position.
b) The pedals will be placed in the most forward position.
c) The bottom 200 mm circle will be placed on the seat bottom such that the distance between the center of this circle and the rearmost face of the pedals is no less than 915 mm (36 inches).
d) The middle 200 mm circle, representing the shoulders, will be positioned on the seat back.
e) The upper 300 mm circle will be positioned no more than 25.4 mm (1 inch) away from the head restraint (i.e. where the driver's helmet would normally be located while driving).

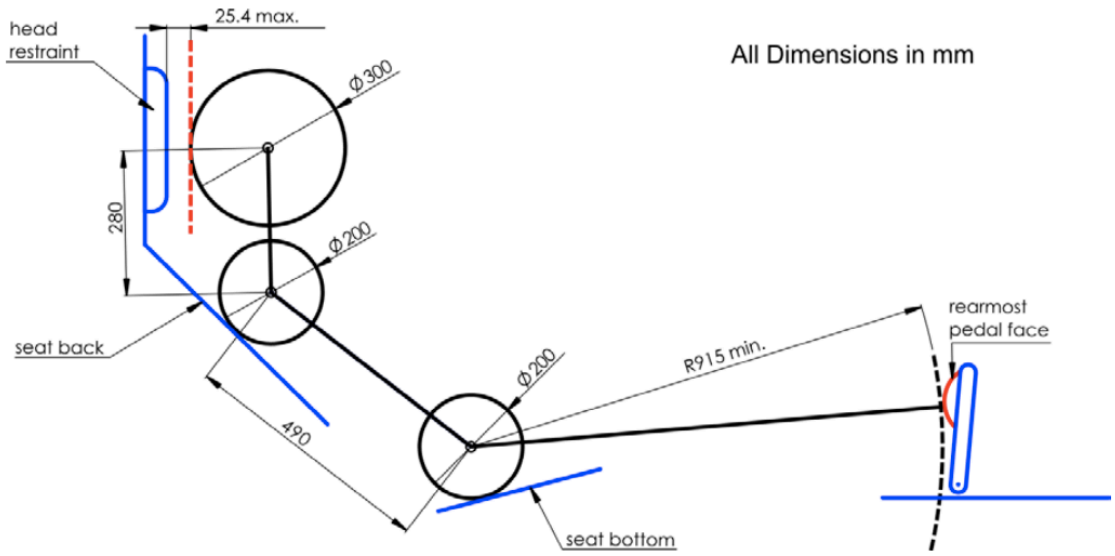

Figure 1. FSAE 95th percentile male template (SAE International 2014).

T3.10.4 aided in determining the location of certain body parts and the lengths between locations on the body for the creation of the posture for the 95th percentile male manikins. It was determined that the line extending from the neck to the top of the head should be parallel to the vertical, or the manikin should be looking forward at 0° from the horizontal (i.e., the neck should be at 90°). The shoulder should be against the seat back and the buttock should be against the seat bottom. The distance from the hip joint to the toe should be 915 mm (the minimum value within the rules).

There are other measurements and locations that T3.10.4 does not include such as information about the arm placement, angle of the seat back, and angle of the foot on the pedal. This information was determined from external sources. The angle of the seat back was determined to be 50° from the horizontal by studies completed by two separate groups of FSAE students (Davies 2012, Mariotti 2000). The angle of the pedals was determined to be 85° from a study completed by Japanese FSAE students and a comprehensive literature review by Schmidt and associates (Hiroshi 2007, Schmidt 2014). The work by Schmidt and associates was also used to determine the positioning of the arm. Within the front view, the legs and elbows were assumed to be approximated shoulder width apart and the hands were placed approximately a steering wheel distance apart.

A full synopsis of the angles and lengths used within the posture can be found in Tables 2 and 3 and an explanation of how the angles and lengths were measured can be found in Figure 2. Within the tables and figures, “hip to toe” refers to the distance between the bottom 200 mm circle to the pedal, “hip to shoulder” refers to the distance between the 200 mm circles, and “shoulder to center of head” refers to the distance between the upper 200 mm circle and the 300 mm circle. Note that there is a range for the knee angle across the manikins. This is due to the different leg lengths among people of the same height. In order to keep the distance from the hip to the toe constant across all manikins, the knee angle had to be adjusted accordingly. A comparison of the other two target lengths to the actual lengths was completed and will be explained later. A sample of a 95th percentile male manikin in the FSAE posture is available in Figure 3.

Table 2. FSAE Posture Lengths.

End Points	Variable on Image	Length (mm)
Shoulder to Center of Head	g	280
Shoulder to Hip	h	490
Hip to Toes	i	915

Table 3. FSAE Joint Angles.

Joint	Variable	Angle (degree)
Neck	a	90
Shoulder	b	55
Elbow	c	116
Hip	d	50
Knee	e	120-125
Ankle	f	85

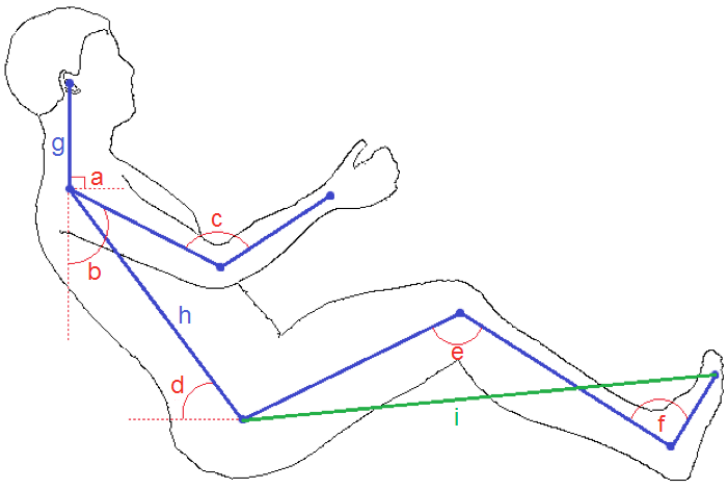

Figure 2. Driving posture for the 95th percentile male.

Currently, there are no requirements detailing the posturing of a 5th percentile female. As a result, the female manikins were postured partially using angles retrieved from the male posture. The upper body was postured using these angles. The arms were postured such that the hands were the same distance from the shoulder as the male manikins (changing the shoulder and elbow angles). The legs were positioned so the distance from hip to toe was 78 cm (changing the hip, shoulder, and ankle angles). This length was determined based on 13.5 cm (approximately 5 inches) of pedal adjustability within the car. A postured 5th percentile female manikin can be seen in Figure 3b.

When comparing the male front and side views to the female front and side views, these images are scaled to the same percentage such that the images are representative of the dimensional differences between a 95th percentile male and a 5th percentile female; the male appears to be much larger than the female in a side by side comparison.

4. Verifying the Posture

The created posture will slightly differ from manikin to manikin due to the different anthropometric measurements. For example, the locations of landmarks, such as the hip joint or shoulder joint, will vary across the 95th percentile males. Due to this shift of joints, the individual manikins needed to be verified to check that they met the criteria set forth in the FSAE rules. This was completed by comparing the dimensions of each manikin to those in Table 3 above. These dimensions were determined by obtaining the location of joints within the Jack software and calculating the distance between the joints. The only location that does not have a joint within Jack is the center of the head. The joint used for this location

was the ear. Table 4 documents the calculated distances between the joints. Since the angles of the joints are set within the Jack software to create the posture, it was not necessary to validate these values. They automatically fit the angles given above in Table 2. Only the male manikins were verified since there are not parameters for the 5th percentile female set forth by FSAE.

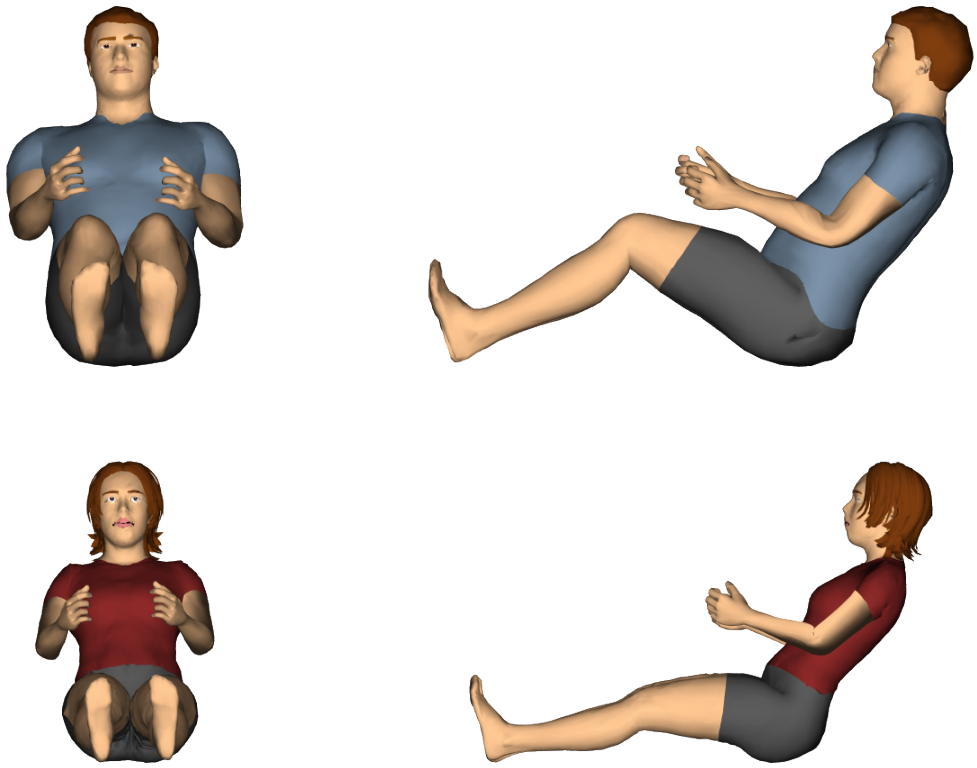

Figure 3. MM1 and FM1 in the FSAE posture.

Table 4. Verification of validity of posture.

	Target Values	MM1	MM2	MM3
Hip to shoulder length	490	490.70	485.86	503.32
Hip to toe length	915	914.99	915.05	915.01
Shoulder to ear length	280	250.12	257.41	250.11

From this verification, it is evident that all manikins meet the hip to toe length parameter. This is because the knee angle was adjusted accordingly such that this parameter was met. The hip to shoulder length value is almost exact for MM1, was slightly smaller for MM2 and was over a cm larger for MM3 Manikin MM2 represents a 95th percentile man with a slightly short torso, decreasing the distance from the hip to the shoulder while MM3 represents the other side of the spectrum, or a person with a long torso. The shoulder to center of head value is 20-30 mm smaller than the parameter that needs to be met of 280 mm. This distance will increase when the upper point is taken as the center of the helmet as intended within the rules. The parameter given in the rulebook gives an upper circle diameter of 300 mm. The maximum head circumference of any of the manikins is 629 mm, which translates to a head diameter of approximately 200 mm. When a helmet is added, this diameter will increase. Examples of the manikins within the Pennsylvania State University (University Park) FSAE team's frame design from 2014 can be found in Figure 5.

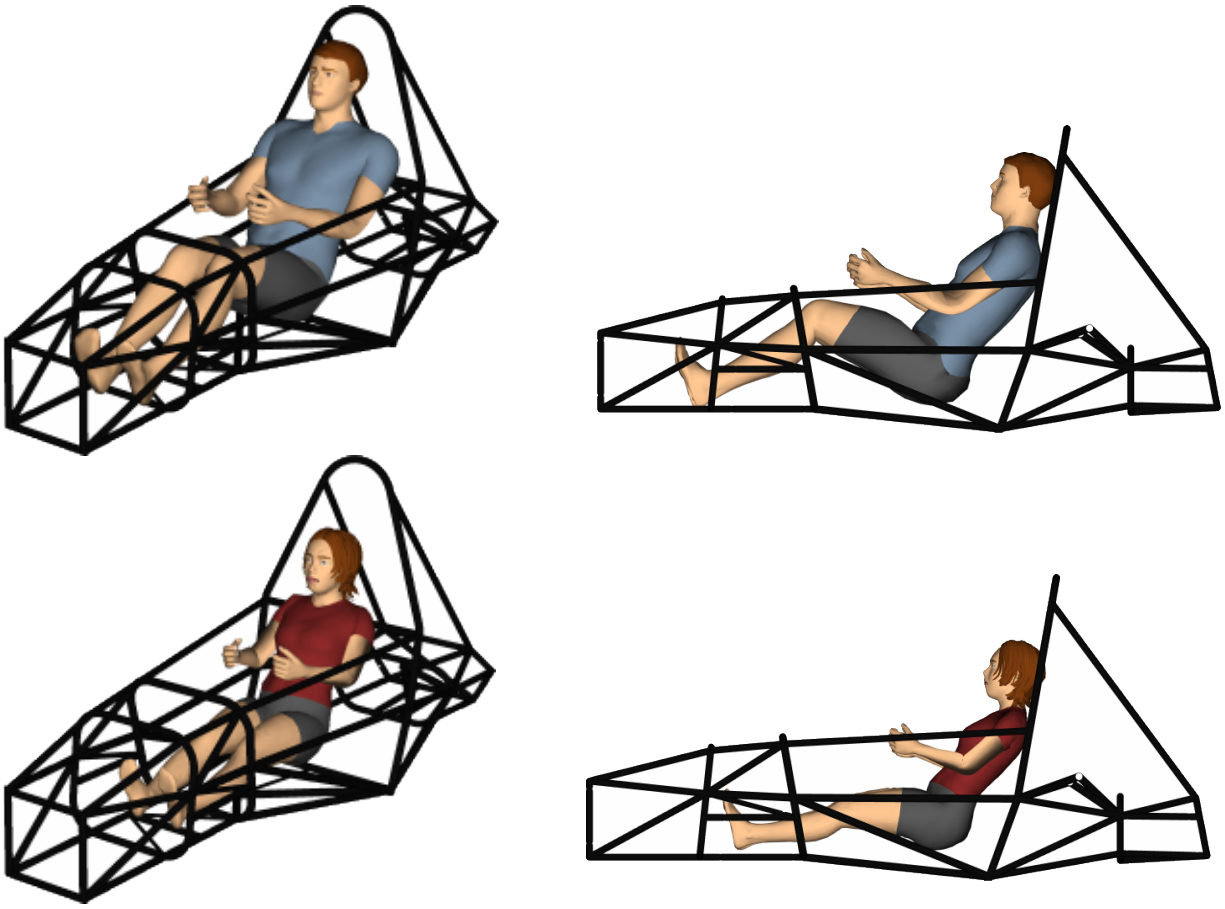

Figure 5. MM1 and FM1 in the FSAE posture.

Overall, the manikins adequately represent the 95th percentile man and the parameters given in the rulebook. The manikin that best represents the rules is MM1. It has precisely the hip to toe length and hip to shoulder length that is stated in the rulebook. The other manikins should not be discarded though. Since there is a large amount of relevant variance for individual measurements for a given height, the other manikins are examples of this possible variance.

5. Limitations and Future Work

The manikins created for use within FSAE vehicles accurately represent 5th and 95th percentile people by stature within current US population. These manikins provide a good approximation of how a person of either of those statures would fit within a FSAE vehicle cockpit. This tool will assist students in creating a vehicle that meets the guidelines for user accommodation.

While these manikins provide the FSAE teams a helpful design tool, the teams cannot rely entirely on the manikins to create a design that accommodates drivers of different sizes. FSAE teams will have to consider many other aspects when creating their cockpit designs. Equipment choices could potentially affect how the driver fits into cockpit. For instance, these manikins are shown without helmets. Variances in helmet size, fire suit thickness, boots, and gloves could have a negative impact on driver fit in a design that is created to exactly fit these manikins. When a helmet is added, this may negatively affect the angle of the neck (driver cannot look forward due to size) or the location of the center of the head (driver's head may extend outside of the roll cage). These issues could mean a violation of the rule

and a disqualification from certain aspects of the competition. The addition of equipment such as the fire retardant suit or boots could mean a driver is now too large to fit into the cockpit if it is designed to just meet the requirements of rule T3.10.4. The design of the cockpit needs to take into account this added bulk.

Another design consideration is how well a car designed toward the 95th percentile US male fits the population of different regions that use these rules. As stated above, the design series is active in Japan, Australasia, Brazil, Italy, the UK, Austria, and Germany. Each of these locations use the same set of rules with some addenda. The only location's addendum that mentions changes to rule T3.10.4 is Australasia's. Within this addendum, it states that the 914 mm from hip to toe must be maintained and if it is not or other sections of T3.10.4 are not met, the team will have a deduction of points and will not be allowed to compete in the dynamic events until the car is modified to comply (Australasia 2014). This differs from the original rules with respect to how the vehicle is judged and that students have a chance to modify the car until it complies with the rules. Since each of the above regions' populations will have a different 95th percentile height for males, compliant vehicles might have cockpits that are much larger or smaller than the local population. If the rules are modified to be location-specific, additional manikins will be required.

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