Analysis of Driver Knee Contours for Vehicle Interior Design

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16. Abstract

An analysis of knee contours was conducted to provide design guidelines to prevent inadvertent actuation of switches located in the lower part of the driver compartment. A programmatic analysis of 3D laser scan data from 181 men and women was conducted. The results quantified the maximum level of penetration into a circular opening that could be expected. The maximum penetration was generally observed in the lateral patella area. A statistical model of the data was used to generate plots of the distributions of penetrations that would be observed for circular holes of various size. A verification study was conducted using manual measurements on a convenience sample of 42 people. The results of the manual measurements were generally consistent with the programmatic measurements from 3D scans, with discrepancies typically less than 3 mm for holes up to 50 mm.

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Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
In	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
Yd	yards	0.914	meters	m
Mi	miles	1.61	kilometers	km
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N

lbf/in^2	poundforce per square inch	6.89		kilopascals	kPa
LENGTH					
mm	millimeters	0.039		inches	in
m	meters	3.28		feet	ft
m	meters	1.09		yards	yd
km	kilometers	0.621		miles	mi
AREA					
mm^2	square millimeters	0.0016		square inches	in^2
m^2	square meters	10.764		square feet	ft^2
m^2	square meters	1.195		square yards	yd^2
ha	hectares	2.47		acres	ac
km^2	square kilometers	0.386		square miles	mi^2
VOLUME					
mL	milliliters	0.034		fluid ounces	fl oz
L	liters	0.264		gallons	gal
m^3	cubic meters	35.314		cubic feet	ft^3
m^3	cubic meters	1.307		cubic yards	yd^3
MASS					
g	grams	0.035		ounces	oz
kg	kilograms	2.202		pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103		short tons (2000 lb)	T
TEMPERATURE (exact degrees)					
ºC	Celsius	1.8C+32		Fahrenheit	ºF
FORCE and PRESSURE or STRESS					
N	Newtons	0.225		poundforce	lbf
kPa	Kilopascals	0.145		poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CONTENTS

ABSTRACT

An analysis of knee contours was conducted to provide design guidelines to prevent inadvertent actuation of switches located in the lower part of the driver compartment. A programmatic analysis of 3D laser scan data from 181 men and women was conducted. The results quantified the maximum level of penetration into a circular opening that could be expected. The maximum penetration was generally observed in the lateral patella area. A statistical model of the data was used to generate plots of the distributions of penetrations that would be observed for circular holes of various size. A verification study was conducted using manual measurements on a convenience sample of 42 people. The results of the manual measurements were generally consistent with the programmatic measurements from 3D scans, with discrepancies typically less than 3 mm for holes up to 50 mm.

INTRODUCTION

The design and placement of switches in vehicle interiors must include consideration of the potential for inadvertent activation. For switches located in the lower part of the driver area, contact with the driver's knee is a possibility. The current project considered the situation of push-button switch recessed within a circular opening. The goal of the research was to estimate the depth of switch placement that would be sufficient to greatly reduce or eliminate the possibility of activation by a driver's knee. The research was conducted in two phases. First, a large set of three-dimensional (3D) body surface scan data was queried to estimate the maximum penetration possible with a range of hole sizes. Second, hole penetrations were manually measured for a convenience sample of knees to verify the findings from the 3D scan study.

METHODS — SCAN-BASED MEASUREMENTS

Surface scan data for right knees were extracted from scan data obtained in a large study of driver postures and body shapes. Figure 1 shows the two postures from which the data were extracted. The included knee angle was either 90 or 115 degrees (approximately typical driving posture). Knees were extracted from scans of 181 men and women in the automotive posture and 83 in the 90-degree posture.
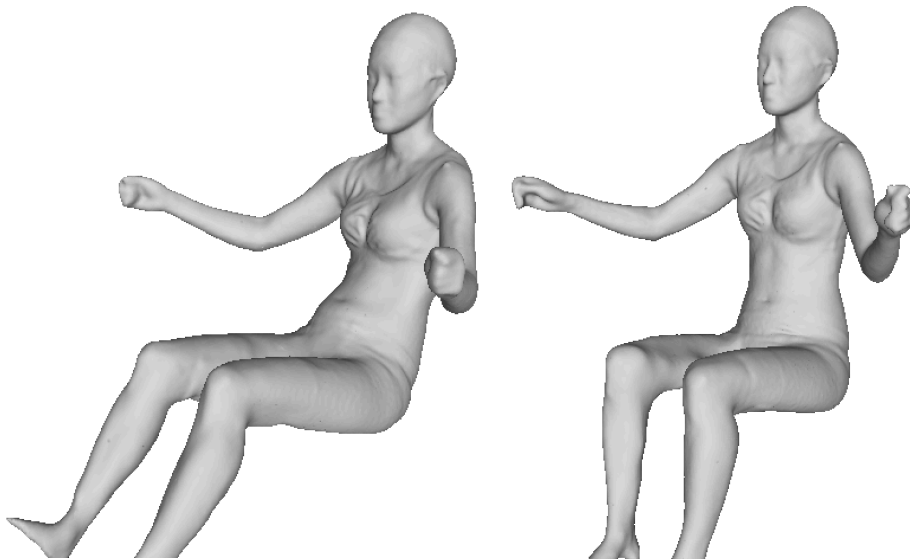

Figure 1. Scan poses used: automotive (left) and 90-degree (right).

For each extracted scan, the locations of four landmarks were available: medial femoral condyle (MFC), lateral femoral condyle (LFC), suprapatella, and infrapatella. These landmark locations are shown in Figure 2. To facilitate programmatic analysis, a rectangular grid was fit to the anterior surface of each scan, using the landmarks to ensure that the grid placement was homologous for each knee.

Figure 2 shows the grid mesh, which was composed of 3111 vertices and is homologous to a half cylinder. In addition to the LFC and MFC landmarks, 12 synthetic landmarks

were generated on the thigh and 12 on the leg to guide the fitting. The suprapatellar landmark was also used to ensure its position would be homologous across fitted scans.
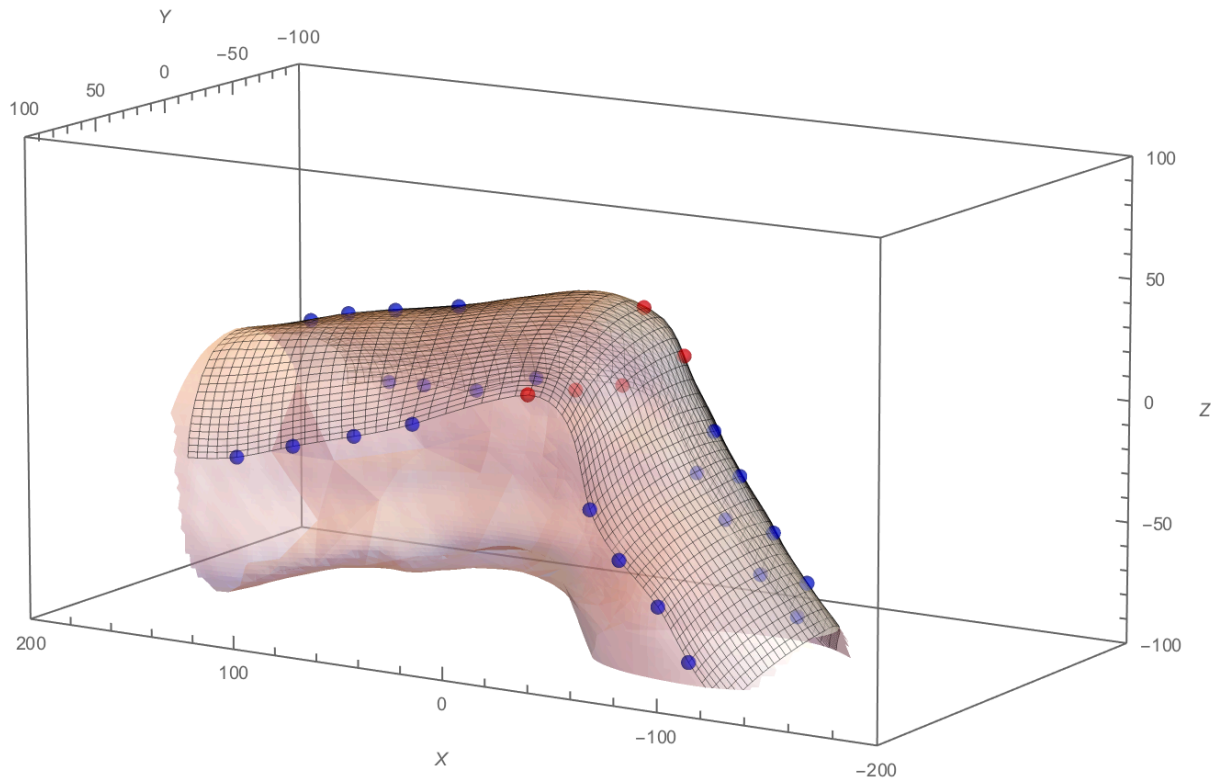

Figure 2. Example of quadrangle mesh (black lines) fit to knee scan. Digitized landmarks are shown in red. Synthetic landmarks used to align the mesh are shown in blue.

Statistical analysis was conducted on the fitted mesh data from the automotive posture. Sex, stature, body mass index (BMI), and sitting height (expressed as the ratio of sitting height to stature, SHS) were included as predictors. Interestingly, stature has very little effect on knee size and shape, holding other variables constant (Figure 3). Sex also has a minimal influence on knee shape (Figure 4). BMI has the largest effect; individuals with high BMI have on average much wider knees (Figure 5).
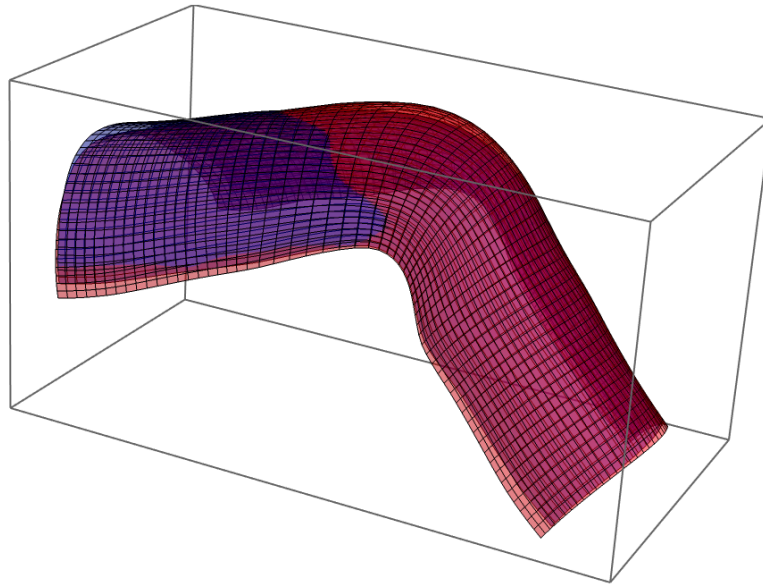
Figure 3. Small female (blue) and large male (red) predicted knee shape holding BMI=27.5 and SHS=0.52. Statures are 1511 and 1870 mm, respectively.
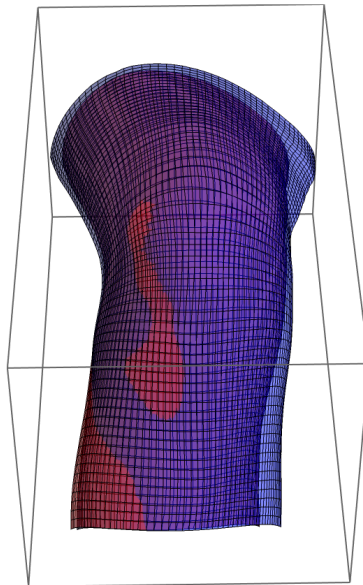

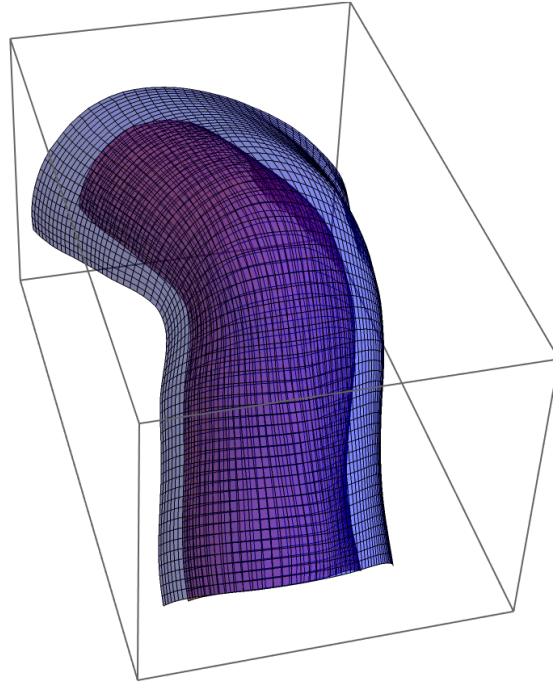Figure 4. Male (red) vs. female (blue) after accounting for stature, BMI, and sitting height.

Figure 5. Mid-stature male with BMI=20 (red) and BMI=35 kg/m^2 (blue).

Simulating Hole Penetration – Automotive Posture

A simulation method was developed to determine how far each knee could penetrate into holes of various sizes. The method is illustrated schematically in Figure 6. For each mesh point in an area near the patella, planar slices were taken along the normal vector at 5-mm increments into the knee. The maximum distance across the slice was determined. This is effectively the diameter of the smallest circular hole into which the knee could penetrate to the specified depth centered on the selected vertex. Repeating this across the knee and taking the smallest slice width for each depth (5, 10, 15, 20, & 25 mm) gives, for each knee, the minimum hole size the knee can penetrate each distance.
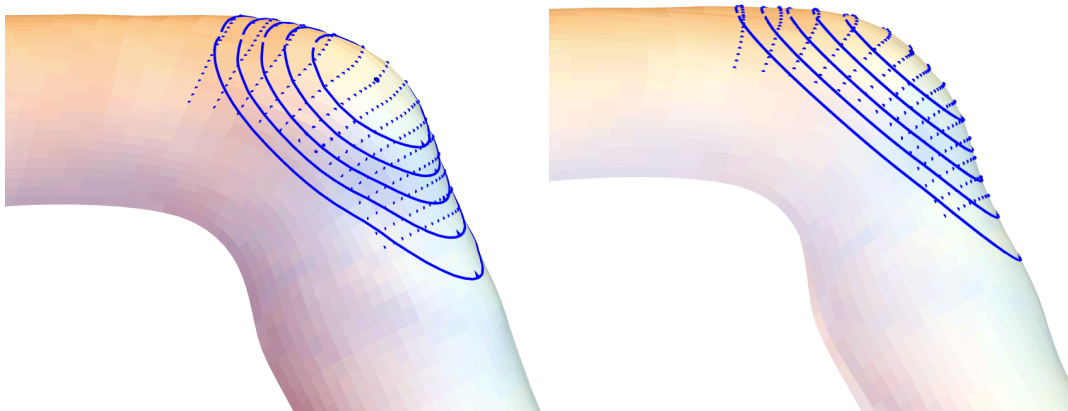
Figure 6. Estimating penetration at 5, 10, 15, 20, and 25-mm increments along the normal for one sample point on the knee (large dot). All sample points are shown with small blue dots.

Figure 7 shows the results from automotive posture scans. The cumulative distributions of across 181 subjects are plotted. The distributions are approximately log-normal. The interpretation of the curves is as follows, for example: approximately a 65-mm-diameter hole is needed to allow 50% of the knees to penetrate at least 10 mm. For that same 65-mm-diameter hole, essentially all knees would be able to penetrate 5 mm, but almost none would penetrate 15 mm or more.
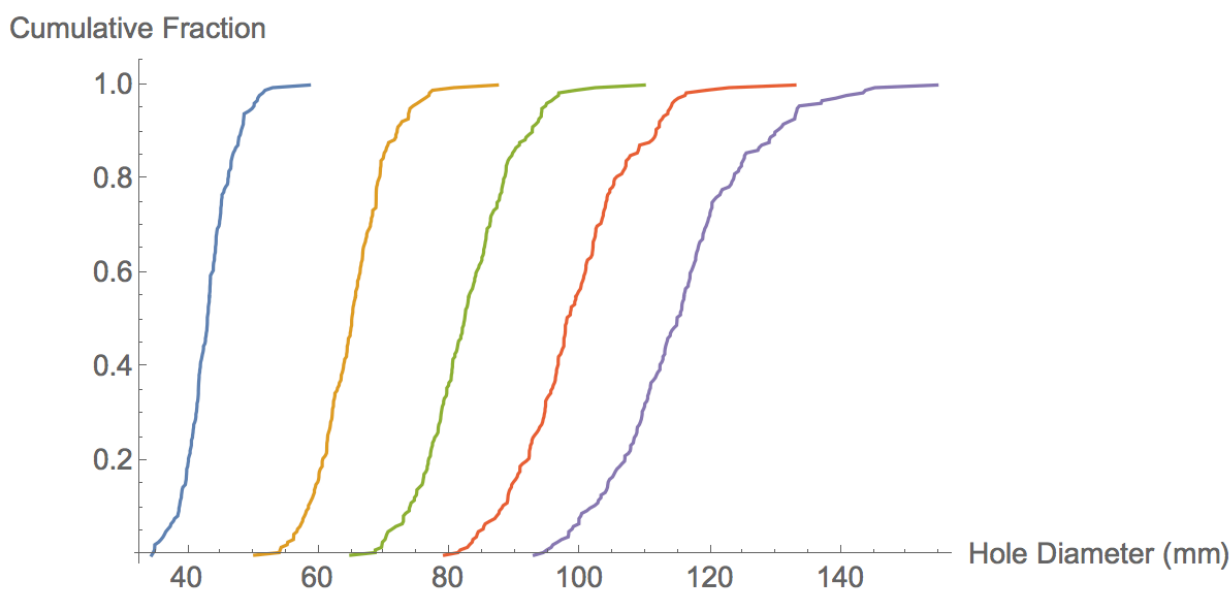
Figure 7. Distributions of the minimum widths for penetrations of 5, 10, 15, 20, and 25-mm (left to right) for 181 men and women.

The areas of greatest penetration (effectively the "pointiest" area of the knee) lay on the outside of the patella area. Figure 8 shows the locations of these sample points on an

exemplar knee. This participant had the smallest max section widths at 10, 15, and 20 mm, effectively showing the highest penetrations (Figure 9).
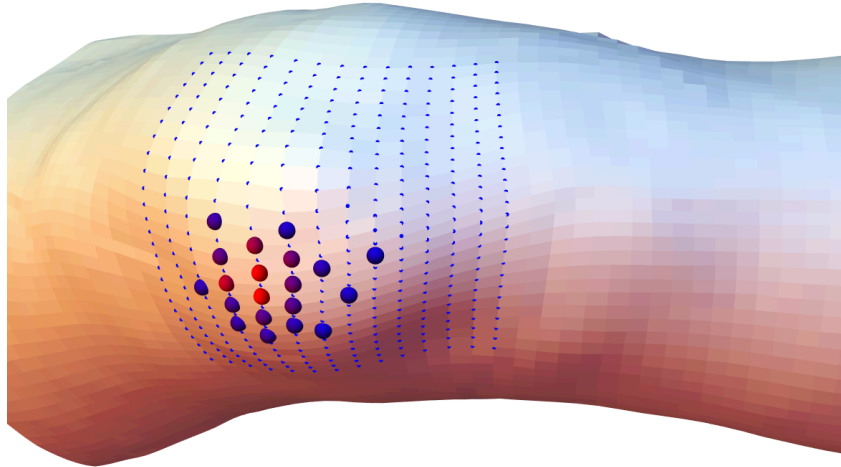

Figure 8. Locations of 10 sample points with the highest penetrations across subjects (smallest diameters at each penetration level) on an exemplar knee. (These are not necessarily the points of highest penetration on this knee.) The lateral aspect is at the bottom of the figure.
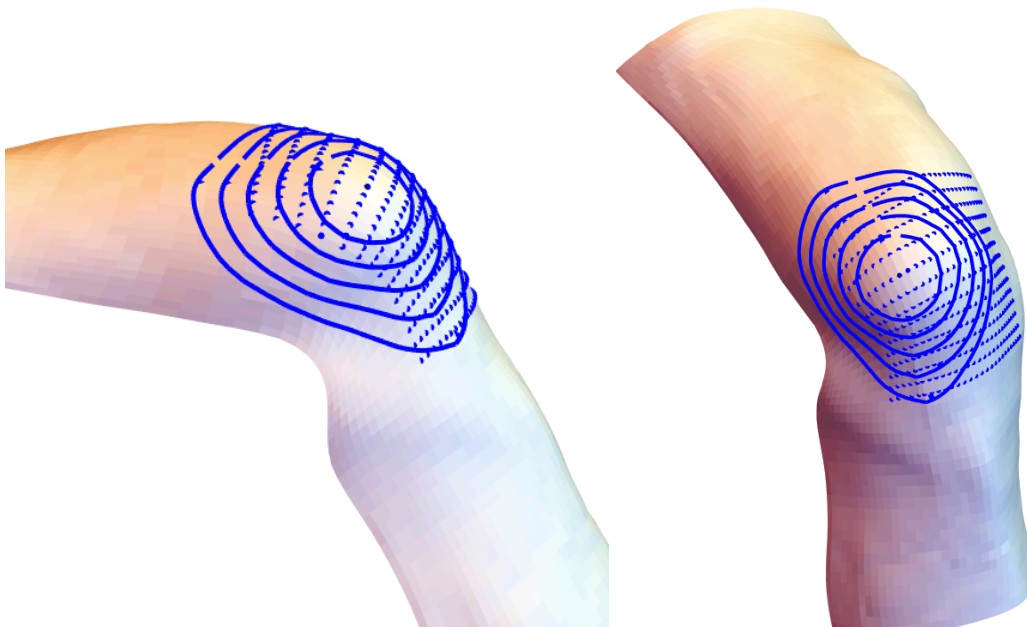

Figure 9. "Pointiest knee", demonstrating the greatest penetrations (subject T098, male, 1699 mm tall, 80 years old, BMI 30.4 kg/m^2).

The most useful predictor of knee penetration depth is body mass index (BMI). Figure 10 shows the minimum hole width for 10 mm penetration as a function of BMI.

This is consistent with the earlier finding that lower BMI is associated with narrower knees, but small stature is not. A consequence of this finding is that further investigation of knee penetrations should focus on low BMI populations, regardless of stature, gender, or age.
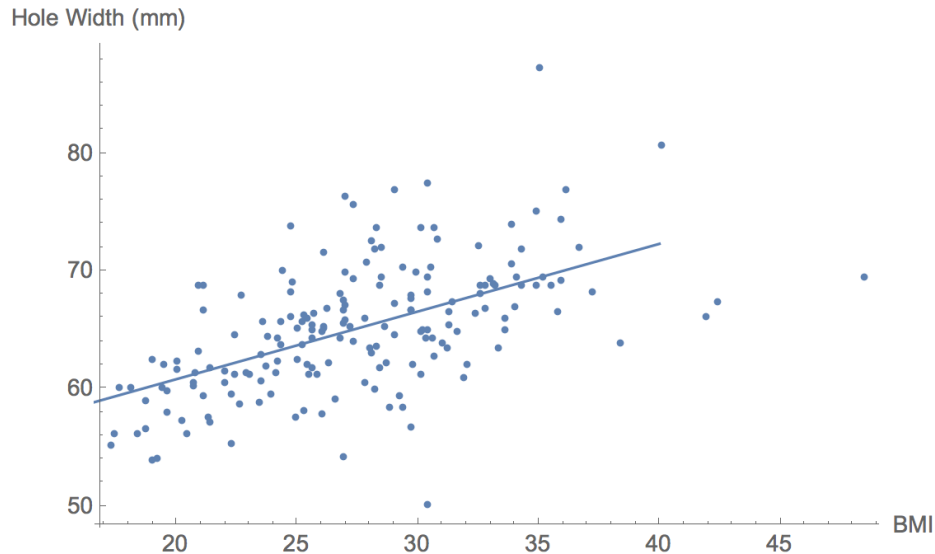

Figure 10. Hole width for 10-mm penetration (smaller indicates greater pointiness) as a function of BMI (kg/m^2). The pointiest-knee subject from Figure 9 is seen here as a low outlier at BMI 30.4.

Simulating Hole Penetration – 90-Degree Posture

The same method used previously was implemented to measure hole penetration with the 90-degree scans. Figure 11 shows the contours on the sample planes for sample point on one knee.

As with the automotive-posture data, the largest width of the plane contour was obtained for each sample point, corresponding to the minimum diameter hole that the knee could penetrate to the prescribed depth at that point. For each penetration depth, the smallest value across the knee was extracted; this corresponds to the smallest hole into which that subject's knee could penetrate by the prescribed amount.

Figure 12 shows these results per sample plane across 83 subjects and provides a comparison with the values obtained using the automotive-like knee flexion (included angle about 115˚). The differences for small amounts of penetration are not large. For example, the median width for 5 mm of penetration is around 45 mm in both postures. Larger differences are observed for greater penetration levels, but at the median the differences are still typically less than 5 mm. The lack of posture effects for small penetrations is because these penetrations are influenced predominantly by the local shape around the patella, which is not strongly affected by knee angle.
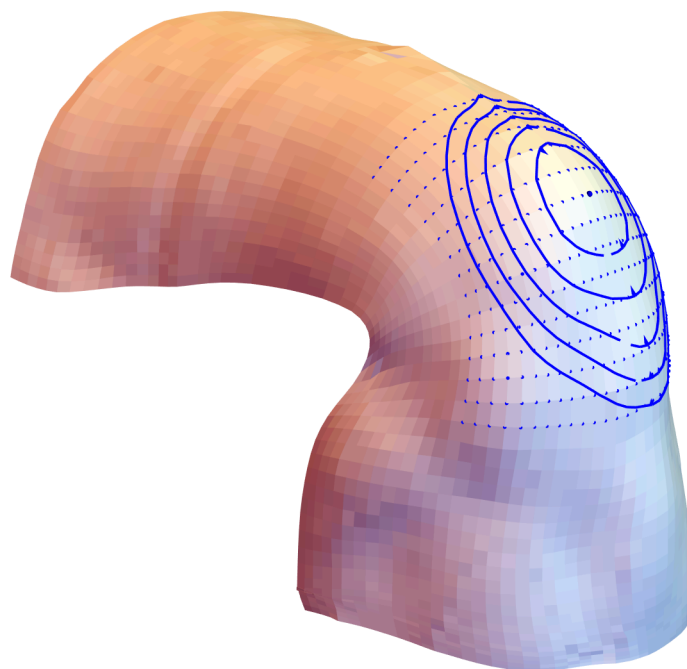
Figure 11. Estimating penetration at 5, 10, 15, 20, and 25-mm increments along the normal for one sample point on the knee (large dot). All sample points are shown with small blue dots.
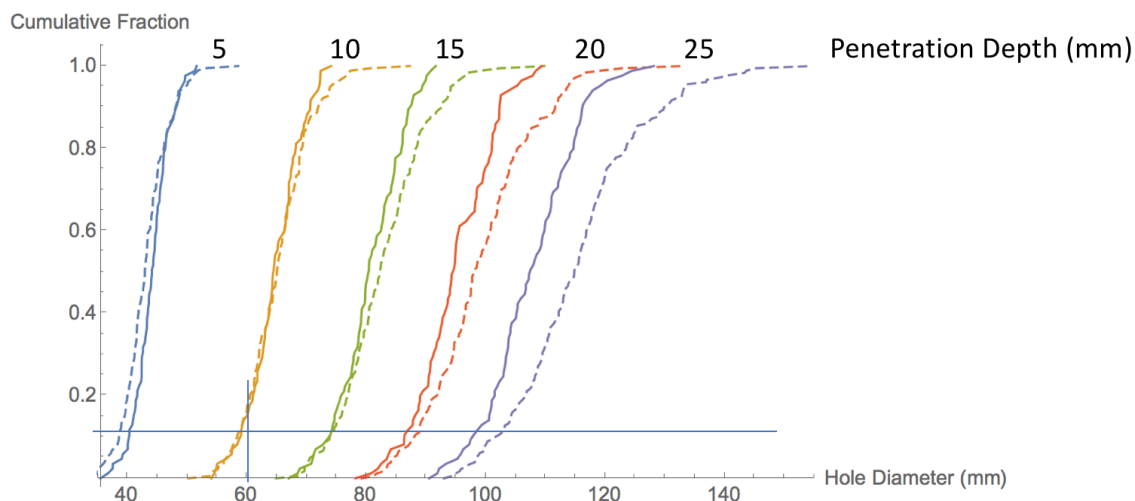

Figure 12. Distributions of the minimum widths for penetrations of 5, 10, 15, 20, and 25-mm (left to right) for 83 men and women with 90-degree included knee angle (dashed lines) and 181 men and women with 115-degree included knee angle (solid lines). Example Interpretation: only about 10% of knees can penetrate more than 10 mm into a 60-mm-diameter hole

As with the previous analysis, the areas of greatest penetration (effectively the pointiest points) lay on the outside of the patella area. One participant had the smallest max section widths at all depths, effectively showing the highest penetrations. This "pointiest knee" is shown in Figure 13. As before, the most useful predictor of knee pointiness (penetration)

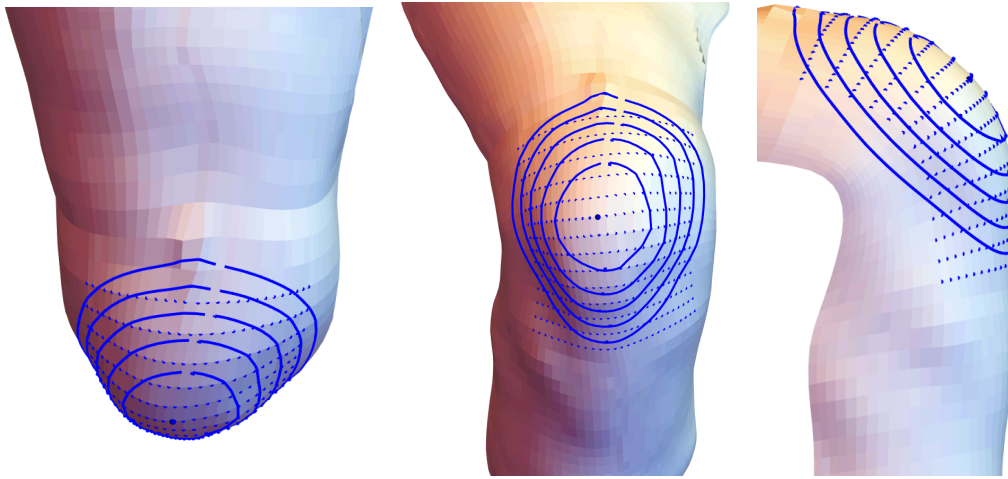is body mass index (BMI). Age and overall body size (stature) had much weaker relationships.

Figure 13. "Pointiest knee" in 90-deg scans, demonstrating the greatest penetrations. (subject T098, male, 1699 mm tall, 80 years old, BMI 30.4 kg/m^2)

The cumulative distributions of hole width for each penetration depth are approximately log-normal. Figure 14 shows log-normal approximations for each penetration depth. Using these distributions, the functions can be inverted to be more useful for analysis. Figure 15 shows the population distribution of penetrations for a range of hole diameters, based on the log-normal fits in Figure 14. The plot shows the distribution of maximum penetrations given the specified hole diameter. For example, consider a penetration of 10 mm. From Figure 15, we expect that nearly all people to require a whole size larger than 50 mm to achieve 10 mm of penetration. In Figure 12, the fraction of the population achieving 10 mm of penetration with a 50-mm hole is close to zero.
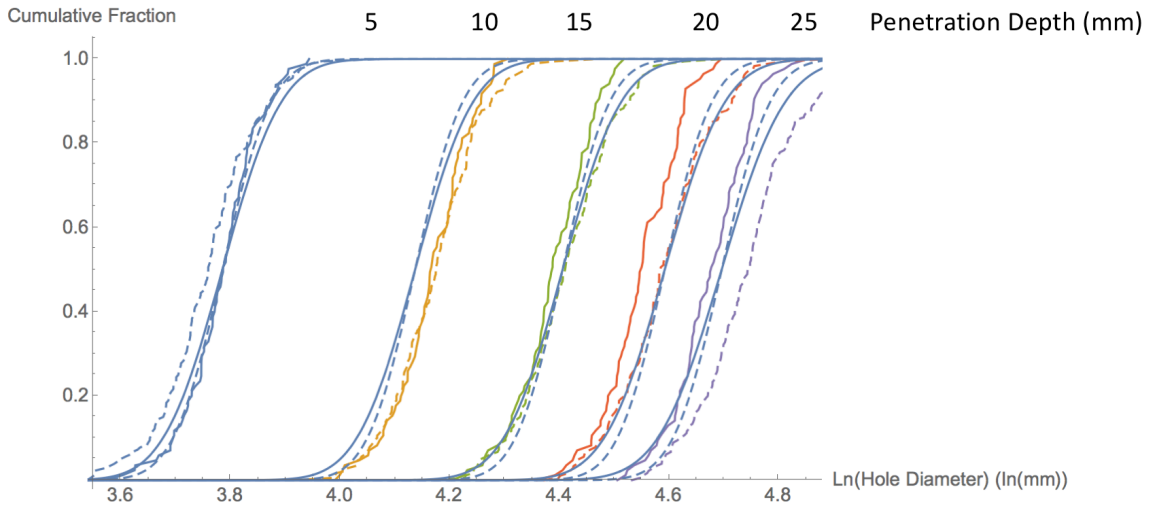
Figure 14. Cumulative log-normal distribution approximations (solid lines) for empirical distributions of hole diameter across penetration depths from Figure 12.
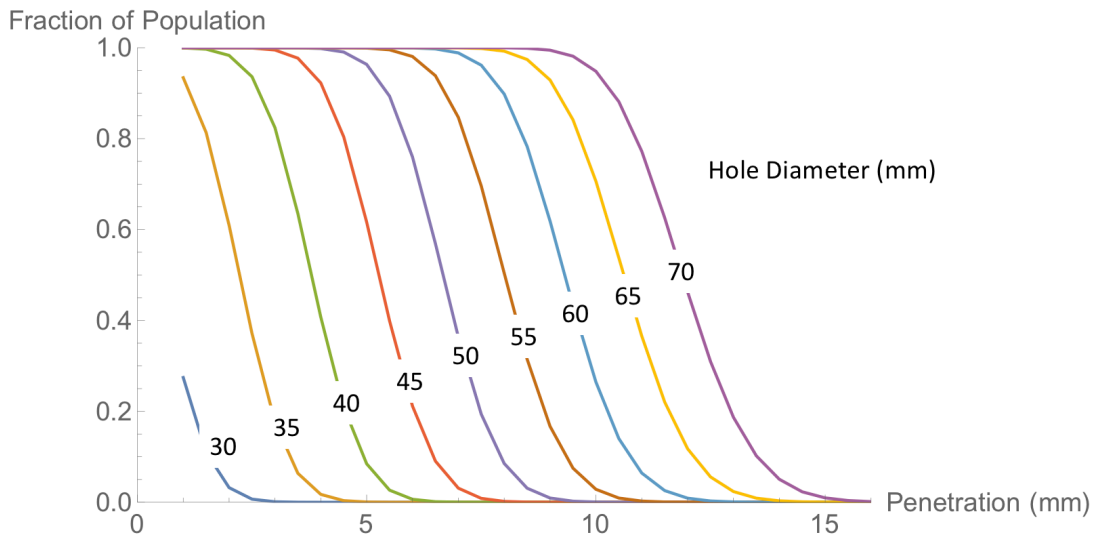

Figure 15. Distribution of penetration depths for a range of hole diameters based on log-normal approximation.

RESULTS – VERIFICATION STUDY

The scan-based analysis provided inexpensive analysis to a large dataset, but the scanning and data processing steps may have tended to smooth the surface, resulting in smaller penetration estimates. Moreover, any effect of soft-tissue deformation would not be captured by the scan-based analysis. Consequently, a small verification study was conducted to compare manual measurements with the scan-based results.

A series of holes were cut in a sheet of 2.25-mm-thick aluminum. As shown in Figure 16, the hole fixture was manipulated to obtain the greatest penetration at each hole diameter from 30 to 70 mm. The penetration was measured to 0.1 mm using a manual depth gage. The fixture thickness was added to each measurement. Data were gathered from a convenience sample of 42 young men and women with a wide range of body size. Figure 18 shows an overview of the participants' characteristics. Data were gathered with people wearing their normal clothing, which included jeans, tights, and no clothing over the knee.
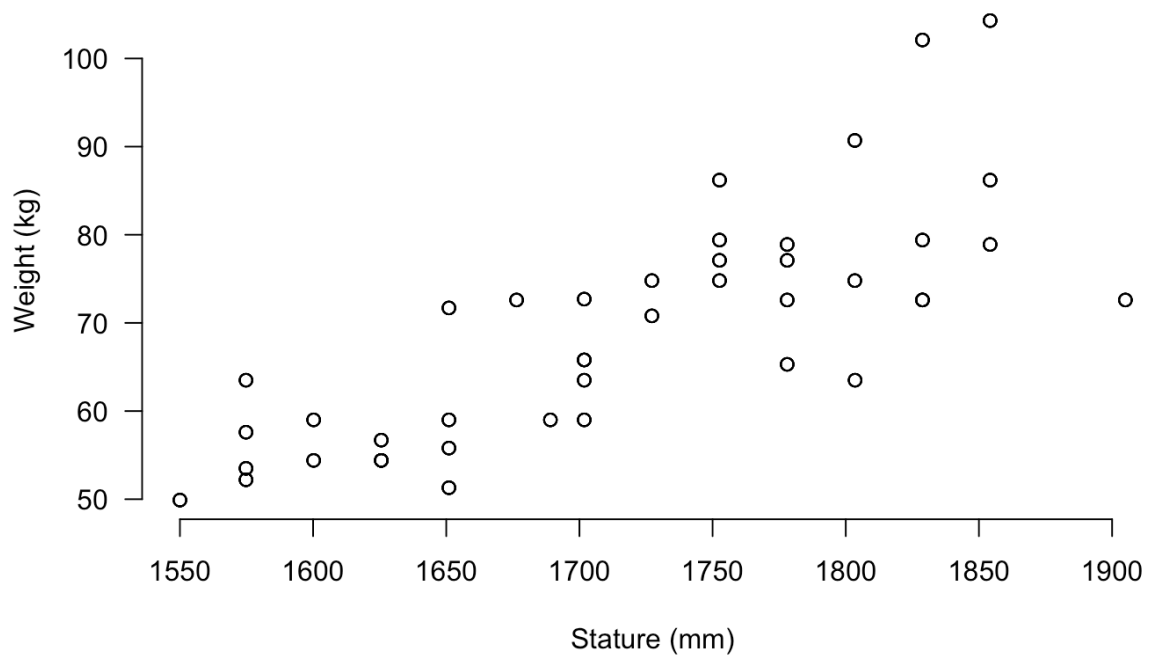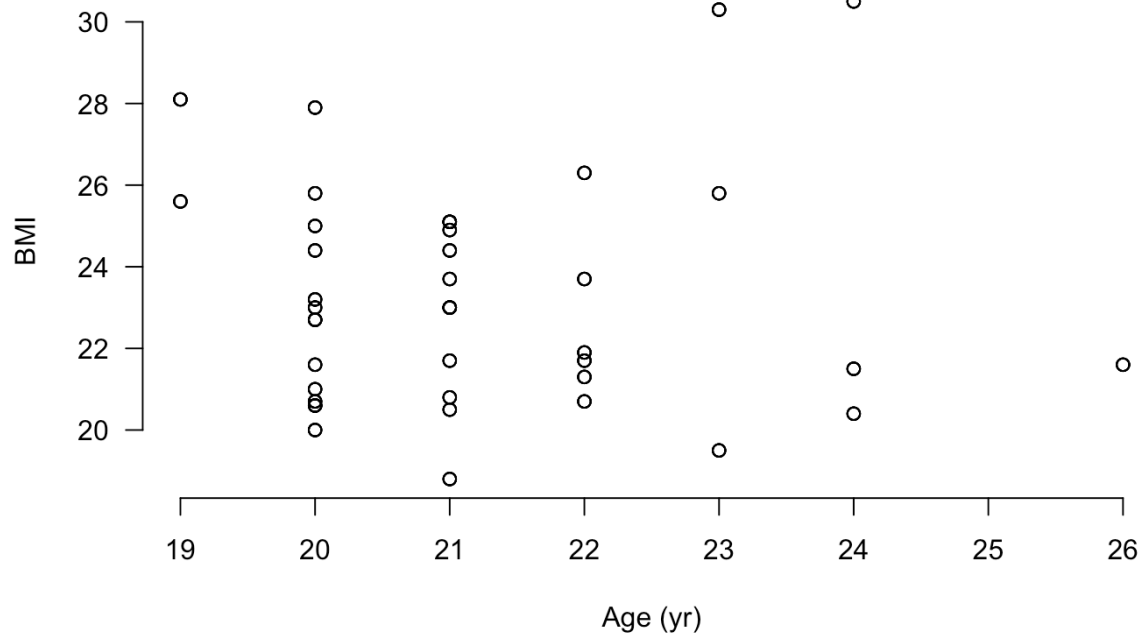

Figure 16. Measuring penetration.

Figure 17. Anthropometric data for N=42 participants in verification study.

Figure 18 shows a boxplot of the data across hole diameter. The distributions within each hole size are approximately symmetrical and the median penetration is an approximately linear function of hole diameter. As in the previous analysis, slightly smaller penetrations were observed for individuals with higher BMI (Figure 19).
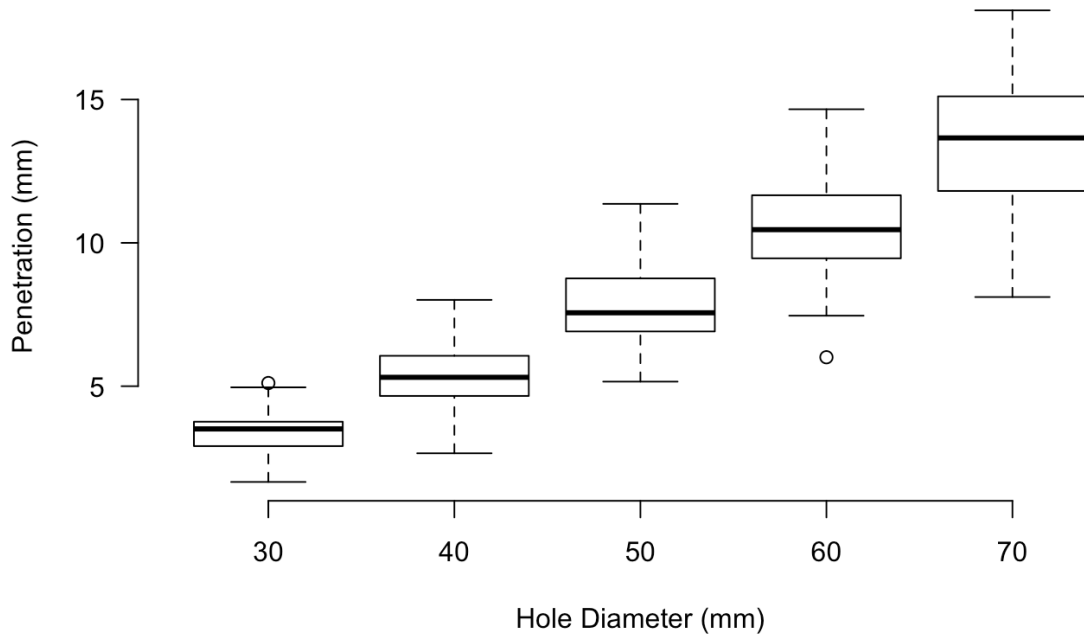

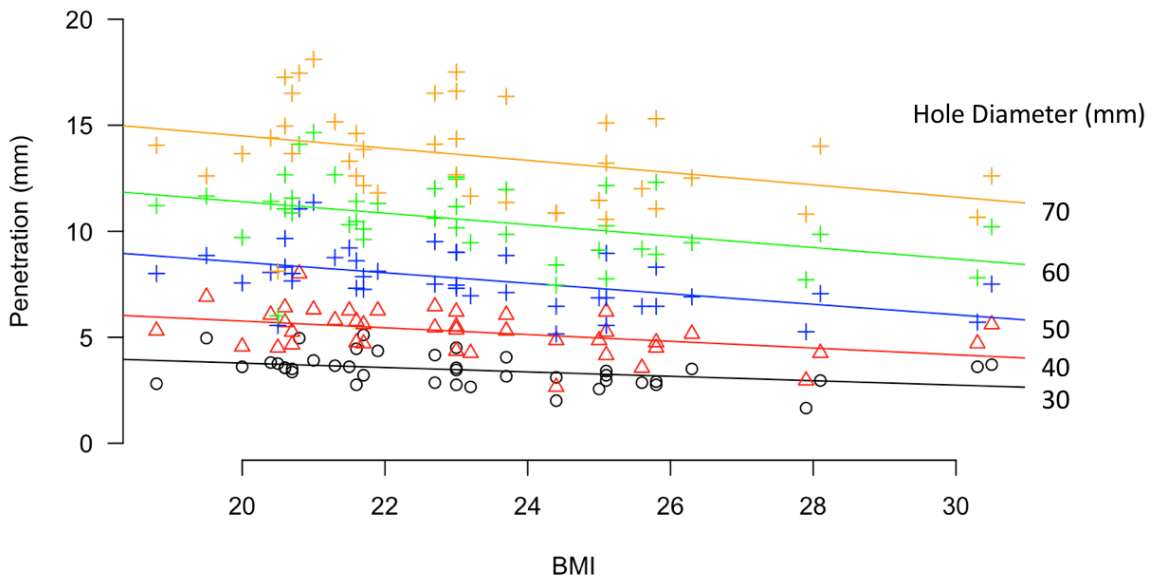Figure 18. Boxplot of measured penetration for a range of hole diameters (N=42 for each diameter).

Figure 19. Effects of BMI on penetration depth in verification dataset.

The distributions of penetration depths can be compared to the estimates from obtained from the scan-based analysis. Figure 20 shows cumulative plots of the manual data (inverted to show fraction exceeding the penetration depth on the horizontal axis). Predictions from the scan-based model (90-deg posture) are also shown. The manual-measurement data show greater penetration than the scan-based model for all hole diameters, but the differences are small in absolute terms. For example, the prediction model shows essentially zero penetrations more than 10 mm for a 40-mm-dimeter hole. The maximum value in the verification data was about 12 mm.
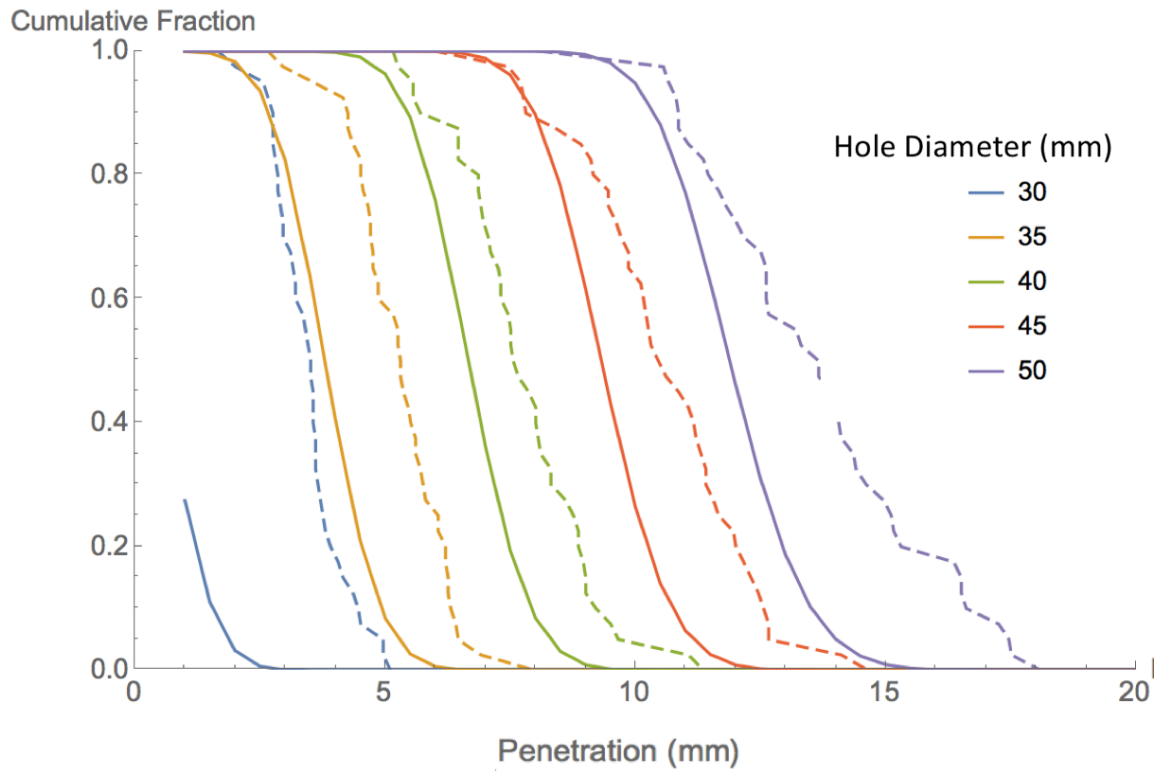

Figure 20. Comparison of verification data (dashed lines) with predictions from scan data (solid lines). The vertical axis is cumulative population fraction exceeding the penetration depth on the horizontal axis for range of hole diameters.

DISCUSSION

The scan-based analysis was largely verified by the manually measured sample. Both methods have some limitations that should be considered. The knees were scanned nude, but as noted above the scanning and analysis process may have smoothed the surface somewhat and flesh deformation is not taken into account. Moreover, the penetration simulation method was based on the local normal. In some circumstances, greater penetration could be obtained using a surface that is not orthogonal to the normal at the center of the simulated hole. The manually measured sample included a range of normal clothing; 16 of the 42 participants wore jeans and 8 had nude knees. Greater penetrations might have been measured if all participants were measured directly on the skin.

Although a weak effect of BMI was observed, no attempt was made to normalize the results to a particular population BMI distribution. The effort is not warranted given that the adjustment is small relative to uncertainties in the BMI distribution.

The parametric models generated in this work can be used to estimate tail percentiles of the penetration distributions. An alternative approach would be to manually measure penetrations for a larger sample of people, specifically targeting those with low BMI, including the youngest and oldest drivers, who are more likely to have lean knees.

The current work does not consider some foreseeable situations, such as individuals with prosthetics or braces on their knees. Further study would be needed to identify the penetrations that could be associated with such devices.