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Exploring the relationship between stride, stature and hand size for forensic assessment

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Exploring the relationship between stride, stature and hand size for forensic assessment

<Anonymous Submission>

Abstract

Forensic evidence often relies on a combination of accurately recorded measurements, estimated measurements from landmark data such as a subject's stature given a known measurement within an image, and inferred data. In this study a novel dataset is used to explore linkages between hand measurements, stature, leg length and stride. These three measurements replicate the type of evidence found in surveillance videos with stride being extracted from an automated gait analysis system. Through correlations and regression modelling, it is possible to generate accurate predictions of stature from hand size, leg length and stride length (and *vice versa*), and to predict leg and stride length from hand size with, or without, stature as an intermediary variable. The study also shows improved accuracy when a subject's sex is known *a-priori*. Our method and models indicate the possibility of calculating or checking relationships between a suspect's physical measurements, particularly when only one component is captured as an accurately recorded measurement.

Introduction

The measurable relationships between different parts of the human body hold widespread interest for the forensic research and practitioner communities. These relationships can be used as part of investigational evidence in a range of scenarios such as video surveillance footage from crime investigation and body identification at mass disaster scenes (Mundorff, 2014).

Three types of measurements are commonly used in investigation. The first represents accurately recorded measurements such as those obtained in custody suites or from physical measurement of a body part or its imprint. The second represents estimated measurement using third-party landmark data. For example, if video evidence is available it may be possible to estimate a person's stature (height) in relation to a known sized object within the image. Finally, the third type of measurement represents inferred data from modelled relationships, either for the purposes of measurement estimation or range confirmation of physically measured characteristics from a particular individual (Scoleri & Henneberg, 2012). For the latter group of measurements, well-defined relationships between measures in a model enable accuracy in prediction, and this can be assessed through the error in model prediction when matched against actual values.

Of interest in a forensic context may be the measurement, estimation, or inference of an individual's height or stature. Indeed, it is a characteristic often reported on by witnesses of victims of a crime, and thus it has real value in suspect apprehension. A range of studies have demonstrated that long bones in the body have a positive linear relationship with stature for different populations across the world (De Mendonca, 2000; Krishan, 2010; Mall et al., 2001; Pelin & Duyar, 2003.

Numerous studies within the forensic and anthropological fields have examined stature prediction from hand features. A series of studies have used the metacarpal lengths, obtained using X-ray images from both right and left hands, in order to estimate stature. For instance, Musgrave and Harneja (1978) obtained regression models based on metacarpal lengths and demonstrated good predictions of stature based on the left metacarpals for digits 1 and 2. Additionally, Habib and Kamal (2010) used the phalangeal lengths from both hands of an Egyptian subject pool and demonstrated that these measurements linked to stature prediction, obtained via a regression model. An earlier study by Sanli et al. (2005) analysed hand breadth and hand length from a Turkish population obtaining three different regressions models for males, females and whole sample populations with smaller model residuals. Since then, a more detailed analysis has been undertaken by Agnihotri et al. (2008) who applied linear and curvilinear regression equations for stature estimation from hand breadth and hand length separately for both sexes within a Mauritian population, whilst three studies (Krishan & Sharma, 2007; Krishan et al., 2012; Sen et al. 2014) have used linear and multiple regression modelling to examine the relationship between stature and hand/feet dimensions within a North Indian population. These latter three studies illustrated the effectiveness of using overall hand and feet dimensions as well as individual component lengths to predict stature. It is clear that, whilst the model coefficients vary within populations, the underlying features considered to be reliable when predicting stature, are consistent.

Most recently, Jee and Yun (2015) expanded the range of hand length features to a total of 29 variables, including hand length and breadth, hand thicknesses and circumferences of fingers, palms and wrists. In order to analyse this expanded set, a multilinear regression analysis with stepwise feature selection was used.

Table 1 shows the adjusted R^2 and RMSE values obtained from each study, alongside the regression model and number of subjects in the dataset. R^2 measures how well the regression model approximates the real data, with a value of 1 indicating that the model fits the data perfectly. RMSE is the sample standard deviation between predicted and observed values. It preserves the original units of measurement, and an RMSE tending toward 0 represents a well-fitting model.

Another fruitful measure which has been used within the forensic field to predict stature is stride length. Studies have shown that the stride length divided by stature is within the range of approximately 0.41 to 0.45 (Hateno, 1993). A mean working ratio for female subjects is 0.413, whilst a working ratio of 0.415 can be used for male subjects (Grieve and Gear, 1966), however, in reality, there is variation across a population. When examining the relationship between stride length and stature, one consideration has related to the pace of walking, and thus the calculated length of the stride. Based on a normal walking speed, rather low correlations have been obtained between stature and right foot stride (r = 0.223) and left foot stride (r = 0.225) (Jasuja, 1993). In addition, a high mean error emerged when estimating stature from stride length using a conventional multiplication factor. In a similar vein, Dobbs et al. (1993) also analysed the link between stature and stride length in 144 participants, and concluded that the model for mean stride length explained only 52% of the variance when considering stature. In contrast, Jasuja et al. (1997) examined the relationship between stride length and stature with stride length calculated from fast walking. The authors found that the mean step length in fast walking was longer and more uniform than in normal walking. This discovery led to higher statistical correlation coefficients for the stature model based on fast walking (r=0.43) than on normal walking (r=0.29). However, the range of errors remains similar for both speeds at around 5.5 cm.

Table 1 Accuracy of stature prediction models from hand lengths – previous studies.

First Author	Year	#Participants	Regression Model	Best Adj. R^2	Best RMSE (cm)
Musgrave	1978	166 (120M, 46F)	H_M ~ Left Met1 H_F ~ Left Met2	NR	5.49 (M) 4.70 (F)
Sanli	2005	155 (80M, 75F)	H_{FMW} ~ HL	0.52 (M) 0.49 (F) 0.76 (C)	4.26 (M) 3.49 (F) 4.59 (C)
Krishan	2007	246 (123M, 123F)	H ~ HL + HB	NR*	NR*
Agnihotri	2008	250 (125M, 135F)	H_M ~ HL + HB H_F ~ HL	0.39(M) 0.54(F)	4.80 (M) 4.16 (F)
Habib	2010	159	H_M ~ HL H_F ~ HL + PL	0.49 (M) 0.32 (F)	5.30 (M) 4.54 (F)
Krishan	2012	140 (70M, 70F)	H_M ~ Left 2ndL H_F ~ Left 4thL	0.56(M) 0.37(F)	NR
Sen	2014	500 (250M, 250F)	H_{FMW} ~ 2ndL + 4thL	0.37 (M) 0.46 (F) 0.57 (C)	NR
Jee	2015	321 (167M, 154F)	H_M ~ HL + PalmL + PL H_F ~ HL + MHB + PalmL H_W ~ WC + PalmL + PL	0.43 (M) 0.42(F) 0.64 (C)	4.81 (M) 5.08 (F) 5.72 (C)

M = Male, F = Female, C = Combined male and female
H = Stature

HL = Hand Length, HB = Hand Breadth, PL = Phalange lengths Met = Metacarpal
WC = wrist circumference, MHB = Maximum hand breadth, PalmL = Palm length
NR = Not Reported, 2ndL = 2^{nd} digit length, 4thL = 4^{th} digit length

* SEE (Standard Error of Estimate) reported

Samson et al. (2001) also analysed the importance of stride length and sex when estimating stature. They found an $r^2=0.22$ for a model between stride length and stature for male subjects and an $r^2=0.29$ for a female model. More recently, Kanchan et al. (2015) studied the correlation of stride length with length of the lower leg and stature, based on 142 young adults from India. The authors found only a significant correlation between average stride length and stature for female subjects, however there were no significant correlations within the male cohort or within the population as a whole. The authors explained the lack of correlation by appealing to individual differences in the personal style of walking. Table 2 summarises the aforementioned stride analyses.

Table 2 Accuracy of stature prediction models from stride lengths – previous studies

First Author	Year	#Participants	r or r^2 (*)
Jasuja	1993	--	0.22 (C)
Dobbs	1993	144 (72M, 72F)	NR
Jasuja	1997	198 (198M)	0.43 (Fast) 0.29 (Normal)
Samson	2001	239 (121M, 118F)	0.29(F)* 0.22(M)*
Kanchan	2015	321 (167M, 154F)	0.025 (M) 0.413 (F) 0.159 (C)

M = Male, F = Female, C = Combined male and female   Fast = Fast walking   Normal = Normal walking
NR = Not Reported

As we have shown, a considerable number of studies have used regression modelling to explore the relationship between stature and hand dimensions, and between stature and stride length. By bridging the gap between all three measures, the present paper will potentially provide an additional useful link in evidence triangulation. Given this, the current paper addresses three novel issues: First, the study attempts to model the three-way relationship between stride (and leg) length, hand size and stature across a population of 97 subjects, thereby providing possible inferred evidence within a forensic context. By separately modelling relationships for known male and female subjects, the study aims to assess how the knowledge of sex of subject can impact prediction performance. Second, a model of the direct link between stride length and hand dimensions is established, without knowledge of the stature of the subject. Third, the study assesses the use of automated extraction techniques for stride length and skeletal measurements using a novel skeletal point tracking device. This offers the benefit of providing a set of internally consistent measurements, allowing evaluation of the effectiveness of utilising novel measurement technologies from forensic surveillance scenarios.

Methodology

A Microsoft Kinect device (Microsoft, 2016) was used to provide a novel range of automated features and, as part of this work, the accuracy of the Kinect device was assessed. Data were drawn from the SuperIdentity Stimulus Database (SSD) (<Anonymous>, 2012) which contained hand images, stride patterns, stature and demographic information from each participant. The participants in the SSD were restricted to Caucasians and were aged between 18 and 35 years. 97 participants (47 male and 50 female) from the SSD who provided a self-reported stature were selected for assessment. The data fell into two categories: *self-reported* and *automatically-measured*. Whilst features measured by human measurement (including self-reporting) replicate conventional assessment of forensic information, surveillance scenarios also result in the generation of large datasets which require automated processing methods. In this study a scenario is replicated where a mixture of self-reported, automatically-measured and inferred features is available for each subject. In doing this, it becomes possible to assess the accuracy of automated extraction methods by comparing estimates against actual data (for example, actual stature against inferred stature). This transparency allows the determination of a level of trust in automated measures. It also becomes possible to assess the accuracy of relational modelling between features against ground-truth data.

Automated Stride and Leg Length Measurement

A Microsoft Kinect sensor was used to collect three videos of participants walking left to right and back again three times in front of the camera. Positional data were collected in an indoor environment lit by florescent lighting in the hall. Side-to-side sequences were filmed from a start point at the far right of the field of view with the camera placed 350cm away. Participants were asked to walk to the far right of the field of view, pause, and then turn around and return to the starting point. This was repeated three times, to obtain three video segments of participants walking left to right and three segments of the participant walking right to left. Participants took approximately six steps from one side to the other. The camera recorded both video and real time skeletal tracking points (see Figure 1), which could be used for stride analysis and leg measurement.

The Kinect sampled 20 skeletal position points associated with a subject’s feet, legs, arms, torso, neck and top of head. Sampling proceeded at a rate of 30Hz, with positional data stored in normalised x, y and z coordinates, calibrated in metres. The confidence in obtaining each skeletal point was also denoted as either “tracked” (located in the video), “inferred” (estimated from connected tracked skeletal points) or “not tracked” (skeletal point not located or estimated). Stride length was extracted from the x and y positions of the ankle points, only when both left and right ankle locations at a particular sample point were denoted as “tracked”. A Euclidean distance between left and right ankle points was used to find the stride length. Figure 2a shows the left and right ankle x coordinates across the 450 sample points for a walking sequence from one individual (approximately 15 seconds of walking left to right, followed by right to left, three times). It can be seen from the graph that the subject completed 5.5 walking sequences, starting left-to-right and finishing with a right-to-left sequence. Figure 2b shows the Euclidian distance between ankle locations (using both x and y coordinates). The peaks in this graph indicate local maxima in ankle separation and are used to indicate stride length. ***Stride Length Median*** **(SL_MED)** was calculated in cm by taking a median Euclidean distance of the local maxima across the walking sequence. A median limits the effects of outlying values.

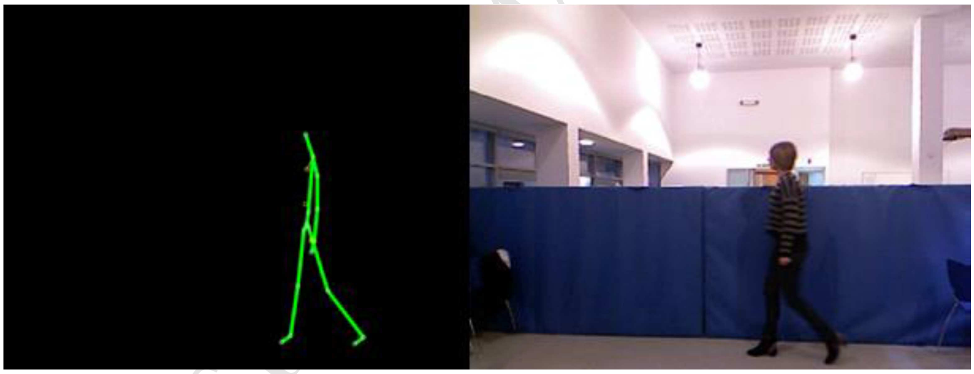

Figure 1: Skeletal points extracted from Kinect video feed

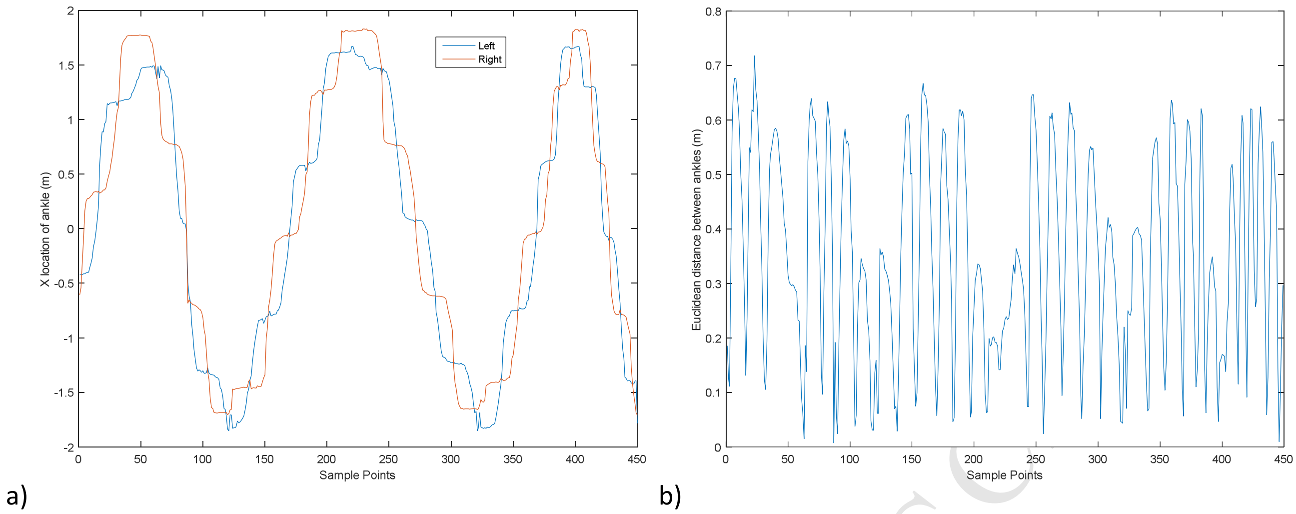

Figure 2: a) Illustrative left and right ankle x coordinates extracted from walking sequence, b) Euclidean distance between ankle x coordinates

Two other features were extracted from the skeletal data:

Leg Length Calculated **(LLC)** was calculated in cm by taking the distance between the median foot y coordinate and the median hip y coordinate when the leg was perpendicular to the floor.

Stature Calculated **(SC)** was calculated in cm by taking the distance between the median foot y coordinate and the median head y coordinate when the leg was perpendicular to the floor.

Reported Measurements of Hand Dimensions

Hand geometry images were captured using a Nikon D200 SLR camera, with both hand and camera facing downwards. Participants placed each hand on an acetate sheet with a series of positioning pegs. Figure 3a shows the rig used to capture images. From each hand image, a series of length measurements (based on the skeleton structure of the hand) were manually extracted (Figure 3b). No significant differences were found between hand dimension sizes of left and right hands therefore, for the purposes of this study, only measurements from the three left hand images were assessed. Table 3 details all the 29 direct and composite measures **(H1-H29)** extracted in cm from each hand.

Reported Stature

As ground-truth data, stature (self-reported) (SSR) in cm was also collected from the participants via an online survey. Our rational behind using SSR alongside Stature Calculated (SC) was to enable a comparison between the results obtained from the automated extraction of stature and physical measurement. If we can identify a significant relationship between SSR and SC then we can utilise the automatically extracted features with confidence for our stature measurement. The SC measurements will also have internal consistency with other features extracted from Kinect measurement. We recognise that in forensic investigations, stature measurements are most often captured in a supervised and controlled manner (although this is also subject to inherent variability). Although SSR is open to larger measurement error, these data within our dataset still provide useful indicators on performance in this proof-of-concept study. The collection of a further dataset involving supervised stature measurement is an element of future work.

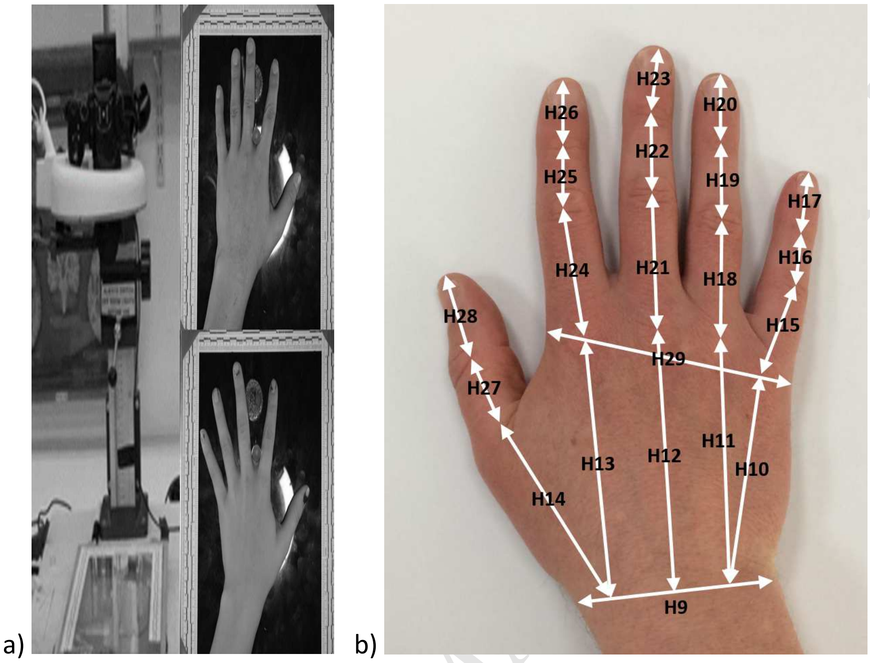

Figure 3: a) Experimental hand image camera rig and b) Component hand dimensions

Table 3: Hand feature set based on component hand dimensions

Feature	Description	Feature	Description
H1	5th digit length (H15 + H16 + H17)	**H16**	Intermediate phalanx of 5th digit
H2	4th digit length (H18 + H18 + H20)	**H17**	Distal phalanx of 5th digit
H3	3rd digit length (H21 + H22 + H23)	**H18**	Proximal phalanx of 4th digit
H4	2nd digit length (H24 + H25 + H26)	**H19**	Intermediate phalanx of 4th digit
H5	1st digit length (H27 + H28)	**H20**	Distal phalanx of 4th digit
H6	Total digital lengths (H1 + H2 + H3 + H4 + H5)	**H21**	Proximal phalanx of 3rd digit
H7	Total metacarpal lengths (H10 + H11 + H12 + H13 + H14)	**H22**	Intermediate phalanx of 3rd digit
H8	Maximum hand length (H12 + H21 + H22 + H23)	**H23**	Distal phalanx of 3rd digit
H9	Wrist breadth	**H24**	Proximal phalanx of 2nd digit
H10	Wrist to 5th digit metacarpophalangeal (MCP)	**H25**	Intermediate phalanx of 2nd digit
H11	Wrist to 4th digit MCP	**H26**	Distal phalanx of 2nd digit
H12	Wrist to 3rd digit MCP	**H27**	Proximal phalanx of 1st digit
H13	Wrist to 2nd digit MCP	**H28**	Distal phalanx of 1st digit
H14	Wrist to 1st digit MCP	**H29**	Max width palm across knuckles
H15	Proximal phalanx of 5th digit		

Results

In this section the individual feature values and their modelled relationship are examined, alongside the forensic application of these models.

Extracted Features

Prior to examining our specific research questions, it was possible to explore the mean feature values and correlation between features. In this way, it was possible to establish baseline anthropological measurements for our cohort, assess measurement relationship to other datasets and also show the related features, providing guidance to subsequent modelling processes. Table 4 shows the mean values from each of the measurements in cm.

Table 4: Mean and standard deviation of feature values across combined, and male and female groups

Variable (cm)	Combined (n=97)		Male (n=47)		Female (n=50)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
SL_MED	58.272	4.394	59.640	4.253	56.987	4.166
LLC	92.719	8.383	97.771	4.968	87.971	8.187
SC	162.294	11.244	169.781	7.334	155.256	9.639
SSR	171.864	10.591	178.332	8.425	165.784	8.677
H1	6.439	0.548	6.751	0.496	6.145	0.419
H2	8.001	0.648	8.370	0.585	7.655	0.499
H3	8.609	0.612	8.983	0.514	8.259	0.475
H4	7.819	0.613	8.142	0.571	7.515	0.485
H5	5.832	0.446	6.059	0.386	5.619	0.393
H6	36.701	2.653	38.305	2.294	35.193	2.014
H7	41.340	3.195	43.275	2.609	39.521	2.577
H8	18.048	1.208	18.825	0.946	17.317	0.946
H9	7.152	0.611	7.548	0.521	6.779	0.429
H10	7.716	0.745	8.095	0.683	7.359	0.617
H11	8.805	0.742	9.185	0.664	8.448	0.629
H12	9.438	0.703	9.843	0.584	9.058	0.587
H13	9.283	0.689	9.692	0.530	8.899	0.597
H14	6.098	0.570	6.461	0.514	5.756	0.379
H15	2.394	0.301	2.509	0.291	2.285	0.272
H16	1.916	0.236	1.990	0.245	1.846	0.205
H17	2.129	0.208	2.251	0.186	2.014	0.155
H18	2.923	0.332	3.070	0.321	2.785	0.282
H19	2.717	0.246	2.821	0.239	2.619	0.211
H20	2.362	0.224	2.479	0.194	2.251	0.194
H21	3.398	0.328	3.564	0.296	3.242	0.279
H22	2.838	0.256	2.964	0.217	2.720	0.234
H23	2.373	0.202	2.455	0.182	2.297	0.192
H24	3.171	0.381	3.329	0.378	3.022	0.321
H25	2.431	0.245	2.537	0.245	2.332	0.202
H26	2.217	0.189	2.276	0.195	2.161	0.166
H27	2.980	0.323	3.112	0.327	2.857	0.268
H28	2.852	0.244	2.947	0.237	2.762	0.217
H29	8.615	0.690	9.020	0.582	8.235	0.558

To determine the extent to which calculated stature differed from self-reported stature, the measures were compared by means of a Pearson's correlation, and a paired samples t-test. The results suggested that whilst the means did significantly differ from one another (t_{98}=13.44, p<0.001), a significantly correlation nevertheless emerged between the two measures r=0.787, p<0.001). In absolute terms, the mean SC value was 9.71cm lower than SSR (95% CI [171.95, 162.24]). Figure 4 shows this relationship across the data. Although there is a difference between the two values, the significant correlation demonstrates the consistency of the measures extracted from the Kinect in relation to actual reported measures. Using the skeletal framework from the Kinect, the other measures from the device that we extract (such as SL_MED) are internally consistent with SC which is used as the sole stature measurement in our modelling.

Table 5 shows the correlation between features for male and female subjects, and for both groups taken together. It is apparent that there are strong correlations between leg length (LLC), stature (SC) and stride length (SL_MED). This process also reveals a number of strong correlations between hand measures and stature, stride length and leg length. H8 (hand length), H3 to H6 (phalange lengths) and H7 (metacarpal length) have strong correlations to LLC, SC and SL_MED within each of the groups, with H8 providing the strongest average correlation.

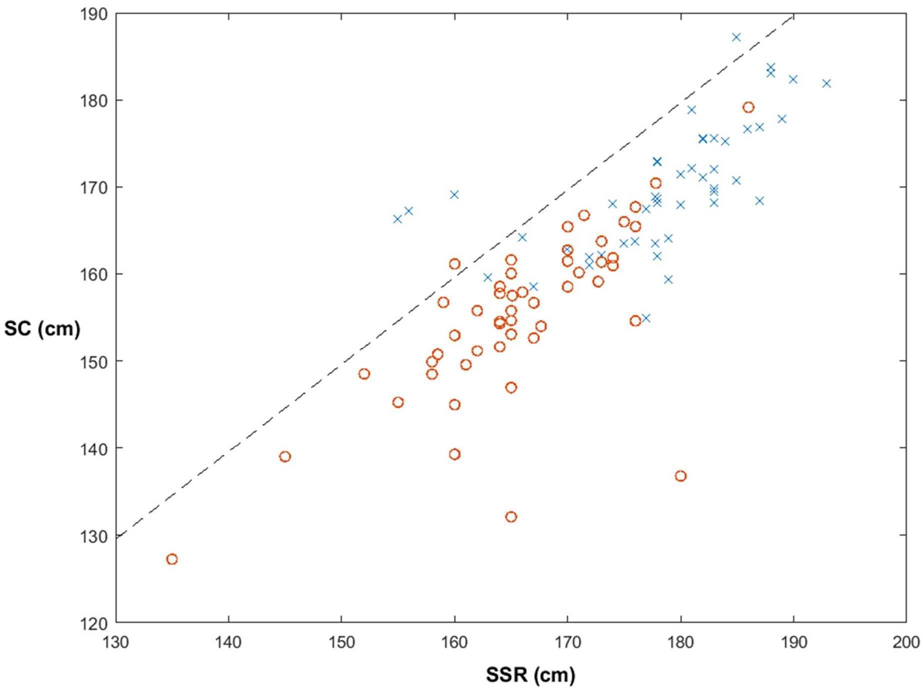

Figure 4: Self-reported stature vs calculated stature. The dashed line shows the ideal correlation between the two variables. (blue crosses=male subjects, red circles=female subjects)

Hand, Stature and Stride Modelling

Table 6a-c shows the best regression models (in term of adjusted R^2) between stride length, calculated stature and hand measurements. Where a particular variable is modelled to the hand variables both the best-fit single variable model and a multi-variable regression are presented. As shown with the correlation results, it can be seen that H8 (hand length) was selected as the modelled hand variable supporting a powerful prediction of other measures in many cases. The best-fit models of hand to leg length and stride length vary in dependant variables when individual sexes are considered, however, again, H8 is the feature with the strongest correlation when both sexes are considered. It can also be seen that the adjusted R^2 values align with models formed in previous studies, thereby validating our methodology of using measurement calculated from the Kinect. Uniquely in this study models have been formed between stature, hand, stride length and leg length across a common population. This enables prediction between these measurements leading to practical use in a forensic context.

Table 5: Correlations between features across combined, and male and female groups

Variable	**Combined**			**Male**			**Female**		
	SL_MED	**SC**	**LLC**	**SL_MED**	**SC**	**LLC**	**SL_MED**	**SC**	**LLC**
SL_MED		0.453**	0.471**		0.316*	0.312*		0.386**	0.439**
LLC	0.471**	0.938**		0.312*	0.909**		0.439**	0.909**	
H1	0.37**	0.557**	0.487**	0.31*	0.315*	0.231	0.192	0.32*	0.266
H2	0.37**	0.622**	0.574**	0.328*	0.385**	0.382**	0.173	0.456**	0.392**
H3	0.425**	0.668**	0.6**	0.352*	0.343*	0.294*	0.287*	0.566**	0.467**
H4	0.421**	0.652**	0.576**	0.283	0.356*	0.232	0.371**	0.622**	0.54**
H5	0.362**	0.599**	0.511**	0.162	0.475**	0.342*	0.344*	0.387**	0.31*
H6	0.423**	0.672**	0.598**	0.327*	0.411**	0.328*	0.307*	0.538**	0.453**
H7	0.411**	0.611**	0.546**	0.222	0.346*	0.334*	0.378**	0.396**	0.303*
H8	0.459**	0.7**	0.626**	0.374**	0.453**	0.405**	0.352*	0.533**	0.43**
H9	0.39**	0.563**	0.481**	0.309*	0.325*	0.35*	0.223	0.216	0.07
H10	0.343**	0.521**	0.493**	0.085	0.235	0.296*	0.39**	0.362**	0.301*
H11	0.406**	0.544**	0.507**	0.233	0.339*	0.355*	0.386**	0.337*	0.292*
H12	0.419**	0.622**	0.554**	0.295*	0.432**	0.398**	0.336*	0.402**	0.316*
H13	0.426**	0.637**	0.552**	0.287	0.447**	0.409**	0.353*	0.409**	0.286*
H14	0.293**	0.499**	0.406**	0.083	0.052	-0.029	0.218	0.279*	0.148
H15	0.257*	0.309**	0.262**	0.237	0.035	-0.004	0.086	0.142	0.098
H16	0.209*	0.386**	0.35**	0.148	0.293*	0.279	0.105	0.24	0.199
H17	0.365**	0.583**	0.508**	0.261	0.399**	0.254	0.228	0.3*	0.284*
H18	0.292**	0.49**	0.429**	0.276	0.32*	0.298*	0.092	0.306*	0.224
H19	0.257*	0.45**	0.453**	0.157	0.123	0.18	0.145	0.384**	0.374**
H20	0.355**	0.577**	0.525**	0.339*	0.477**	0.433**	0.155	0.31*	0.277
H21	0.302**	0.518**	0.445**	0.155	0.148	0.108	0.212	0.422**	0.302*
H22	0.301**	0.55**	0.51**	0.259	0.239	0.242	0.121	0.44**	0.374**
H23	0.416**	0.483**	0.447**	0.434**	0.444**	0.367*	0.253	0.249	0.259
H24	0.296**	0.558**	0.474**	0.218	0.286	0.16	0.178	0.558**	0.455**
H25	0.322**	0.457**	0.428**	0.129	0.191	0.229	0.34*	0.348*	0.285*
H26	0.35**	0.399**	0.358**	0.245	0.246	0.082	0.327*	0.314*	0.351*
H27	0.297**	0.503**	0.398**	0.026	0.411**	0.235	0.41**	0.319*	0.238
H28	0.269**	0.429**	0.407**	0.228	0.206	0.232	0.117	0.305*	0.268
H29	0.353**	0.535**	0.466**	0.312*	0.282	0.298*	0.148	0.254	0.147

** significant to < 0.01
* significant to < 0.05

Table 6a) Best fit regression models – combined group

Variables		Both	
Category	**Dependant**	**Adj. R^2**	**Regression**
Hand (single variable)	SC	0.485	SC = 44.626 + 6.52 (H8)
	H8		H8 = 5.834 + 0.075 (SC)
	LLC	0.386	LLC = 14.27 + 4.347 (H8)
	H8		H8 = 9.678 + 0.090 (LLC)
	SL_MED	0.203	SL_MED = 28.115 + 1.671 (H8)
	H8		H8 = 10.686 + 0.126 (SL_MED)
Hand (stepwise)	SC	0.524	SC = 44.288 + 5.254 (H8) + 7.310 (H24)
LLC	SC	0.878	SC = 45.668 + 1.258 (LLC)
	LLC		LLC = -20.743 + 0.699 (SC)
SL_MED	SC	0.197	SC = 94.786 + 1.158 (SL_MED)
	SL_MED		SL_MED = 29.566 + 0.177 (SC)
	LLC	0.214	LLC = 40.306 + 0.899 (SL_MED)
	SL_MED		SL_MED = 35.363 + 0.247 (LLC)

Table 6b) Best fit regression model – male group

Variables		Male	
Category	**Dependant**	**Adj. R^2**	**Regression**
Hand (single variable)	SC	0.21	SC = 125.033 + 18.033 (H20)
	H20		H20 = 0.337 + 0.013 (SC)
	LLC	0.170	LLC = 70.276 + 11.092 (H20)
	H20		H20 = 0.825 + 0.017 (LLC)
	SL_MED	0.171	SL_MED = 34.671 + 10.171 (H23)
	H23		H23 = 1.349 + 0.019 (SL_MED)
Hand (stepwise)	SC	0.272	SC = 113.285 + 14.622 (H20) + 6.508 (H27)
LLC	SC	0.823	SC = 38.506 + 1.343 (LLC)
	LLC		LLC = -6.815 + 0.616 (SC)
SL_MED	SC	0.079	SC = 137.30 + 0.545 (SL_MED)
	SL_MED		SL_MED = 28.549 + 0.183 (SC)
	LLC	0.077	LLC = 79.069 + 0.364 (SL_MED)
	SL_MED		SL_MED = 33.565 + 0.267 (LLC)

Table 6c) Best fit regression model – female group

Variables		Female	
Explanatory	**Dependant**	**Adj. R^2**	**Regression**
Hand (single variable)	SC	0.375	SC = 62.278 + 12.372 (H4)
	H4		H4 = 2.654 + 0.031 (SC)
	LLC	0.278	LLC = 19.402 + 9.125 (H4)
	H4		H4 = 4.7 + 0.032 (LLC)
	SL_MED	0.151	SL_MED = 38.809 + 6.362 (H27)
	H27		H27 = 1.352 + 0.026 (SL_MED)
Hand (stepwise)	SC	0.375	SC = 62.278 + 12.372 (H4)
LLC	SC	0.822	SC = 61.161 + 1.070 (LLC)
	LLC		LLC = -31.844 + 0.772 (SC)
SL_MED	SC	0.131	SC = 104.331 + 0.894 (SL_MED)
	SL_MED		SL_MED = 31.063 + 0.167 (SC)
	LLC	0.176	LLC = 38.784 + 0.862 (SL_MED)
	SL_MED		SL_MED = 37.322 + 0.224 (LLC)

Accuracy of the models for forensic investigations

It is possible to envisage the use of these models under investigative scenarios where one or more facet of identity is available and a test is required on an actual or inferred measurement from the same subject. In a simple case, the modelled properties of stature may be required given a particular known hand measurement (or *vice versa*). If the sex of the subject is known, then the tuned model can be used. When unknown, the 'combined' sexes model can be used. These cases are illustrated as Scenarios 1 – 3 below. Scenario 1 uses models that comprise a *single* hand feature that resulted in the lowest modelled error in predicting stature, whereas Scenario 2 uses models combining *multiple* hand features that resulted in the lowest modelled error. Both these scenarios use model constructed independently for each of the three population groups.

Given the widespread use of CCTV images, a situation may, however, arise where remote measurements of a subject are obtained (for example, a subject's estimated leg or stride length from a video source). Having obtained models linking these facets to stature and hand size, these can be used to form direct (leg to hand, and stride to hand) or indirect (leg/stride to stature to hand) predictions of other characteristics. These cases are illustrated as Scenarios 4 -7 below.

Table 7 shows the RMSE results across these seven scenarios. RMSE is useful in this exercise as the error is expressed in the same units as the modelled target data. Where the target is a feature of the hand (Scenarios 3 to 7) H8 (hand length) was selected as the target feature enabling comparison of RMSEs between the groupings.

Table 7: RMSE of direct and indirect models.

				Combined	**Male**	**Female**
Scenario	**Mode**	**Source**	**Target**	**RMSE (cm)**		
1	Direct	Hand (Single Feature)	Stature	7.983	6.378	7.468
2	Direct	Hand (Multiple Features)	Stature	7.641	6.055	7.468
3	Direct	Stature	Hand Length	0.859	0.837	0.794
4	Indirect	Leg Length via Stature	Hand Length	0.938	0.858	0.848
5	Indirect	Stride Length (Median) via Stature	Hand Length	1.082	0.897	0.889
6	Direct	Leg Length	Hand Length	0.937	1.014	1.096
7	Direct	Stride Length (Median)	Hand Length	1.068	1.268	1.254

In assessing the results in Table 7 it was possible to observe that RMSE values were slightly higher than other studies which may be due to the calculated nature of stature. The hand measurements had a mean residual of between 7 and 12mm. Figure 5a-f displays (left hand figures) the relationship between actual and modelled target results and (right hand figures) the residuals for each subject in each scenario. It was also possible to note that the direct models linking leg/stride length to hand length produce similar residuals relative to when stature was used as an intermediary. An advantage of using the latter is that an additional variable is modelled, adding to the forensic evidence obtained. However, it must be acknowledged that the direct linkage is marginally stronger, thereby providing a trade-off between overall accuracy and quantity of inferred features.

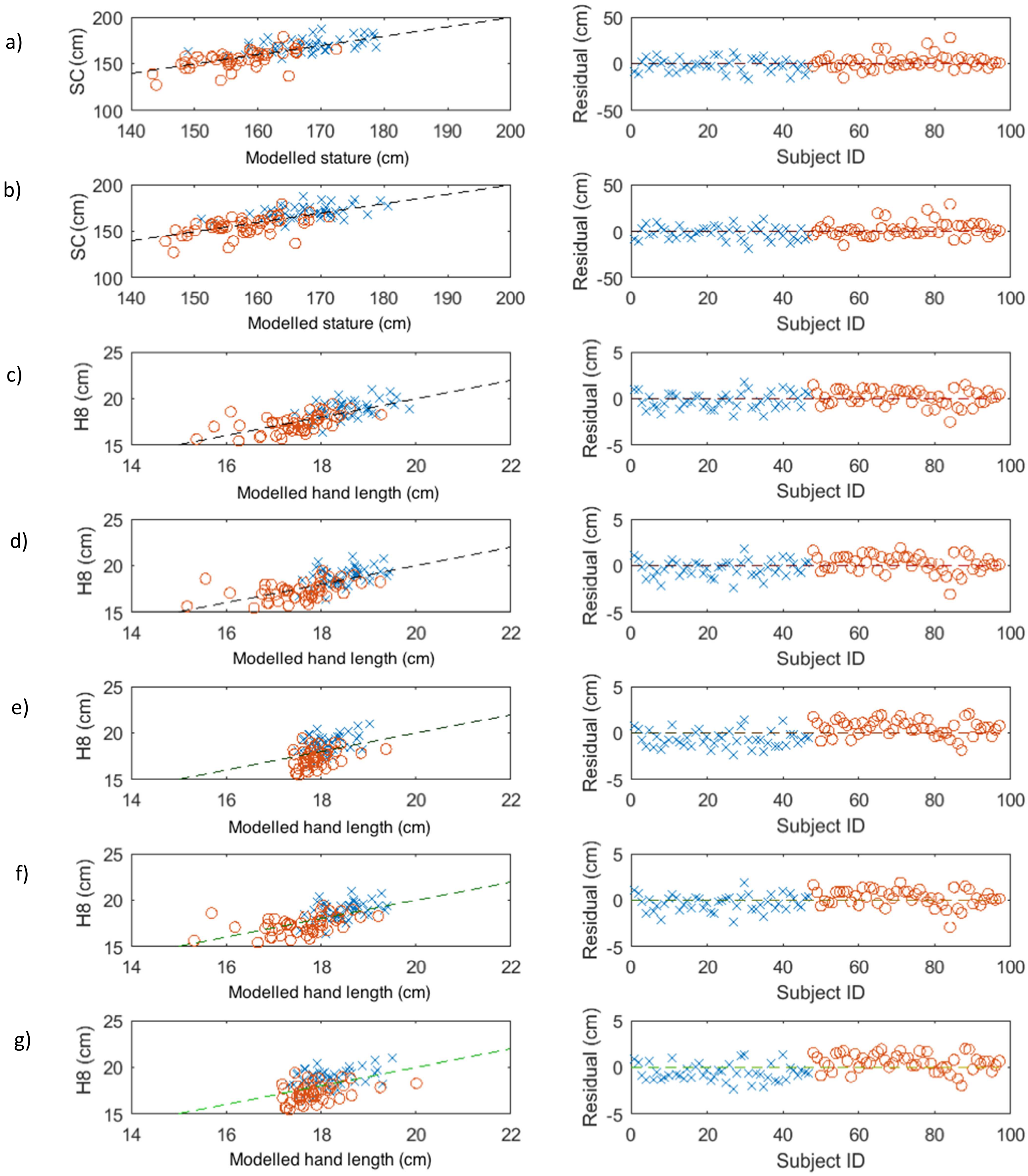

Figure 5: Modelled relationships and individual subject residuals for each of the seven scenarios in Table 7 (blue crosses=male subjects, red circles=female subjects)

Discussion

In comparing our results with previous studies several observations can be made:

The R^2 values from our models are comparable with the results from other studies. However, as our models use calculated stature rather than the self-reported or directly measured stature, a direct comparison of model performance is not strictly applicable. The R^2 values do, however, indicate that the Kinect device has the potential for use in forensic assessment where linkages between body measurements are required. Across all studies, it is important to consider possible differences within a population, together with the size of the population sampled, as this again could lead to inherent differences in regression fit. Inter-study comparisons should focus on the relative size of statistics such as R^2 and the features selected by the modelling process. In this respect, when linking stature to hand measurements, our universal model across both sexes uses overall hand length as a predictive feature, as identified in other work [8, 9 and 10]. However, the current work has used a finer resolution of hand measurements in comparison with previous work. The best feature for the stature to hand regression model for male subjects uses the distal phalanx. This indicates the use of a finer resolution of measurements may lead to optimal results within populations. Our hand to stature model for female subjects uses 2nd digit (index finger) length as identified in Krishnan et al. (2012) and Sen et al. (2014). The slightly higher R^2 values obtained in our studies in comparison with these two studies may be attributed to population differences between studies.

Across the literature, there is a larger variability in the errors contained within models linking stature to stride length. Potential contributing factors to this include the range of intra-person walking styles, and walking speeds. Our R^2 results are, however, comparable to other studies such as Jasuja (1993), Dobbs et al. (1993), and Jasuja et al. (1997). Assessing the modelling relationship between leg length and stride length, a significant correlation did emerge both when the sexes were considered individually and when combined. This is in contrast with the results reported by Jasuja et al. (1997). However, our correlation is less significant in males, which does agree with this study. Overall, there are very strong correlation and model R^2 values for leg length to stature agreeing with the studies of Pelin et al. (2003) and De Mendonca (2000).

As noted in Table 4, self-reported stature (SSR) is greater than calculated stature (SC). This may be explained by three factors: i) subjects typically had their head bowed whilst walking, ii) the Kinect reported head position below the actual top of head and iii) the reported ankle position was above the actual floor. It must also be acknowledged that, due to the self-reported nature of SSR, there are some inherent inaccuracies in measurement. Indeed, subjects, when self-reporting stature, tend to make themselves taller unless they are very tall and then they tend to under report (Spencer et al., 2002).

As the aims of our work included an exploration of automated tools to i) calculate accurate anthropological features and ii) model anthropological and behavioural linkages, the mean and range of extracted features, the correlation significance between features and the accuracy of our models proves that the devices and methods employed within the experiment have the capability for providing accurate and usable results.

Conclusions

Within this work a novel dataset has been used wherein data for hand, stature, stride length and leg length have been captured from a common population. This has allowed unique modelling of the relationships between and across these elements. The resultant models aligned well with other studies linking hand to stature, and stature to stride and leg length. Additionally, the current results suggest that it is possible to use stature as an intermediary measure between hand and stride length, as well as exploiting a direct relationship between these measurements. The intermediary use of stature has the advantage of providing additional modelled information (stature, alongside hand measurements) with no noticeable performance deterioration. The current methodology of using calculated height replicates that used to obtain data from video-based sources where accurate direct physical measurements may not not available. Even with these calculated data, internal accuracy of the current models is achievable, typically to within 8mm of actual hand length. This triangulation between stature, hand and stride/leg length provides a useful analysis for inferring and checking evidence from within a subject's measurements. Within separate models of hand to stature, and stature to leg length measurement, a detailed meta-analysis across different populations and datasets would ascertain the complementary in our modelled relationships. Future work would involve the collection of additional data from a disjoint population to independently validate the models that we have derived. As the use of hand morphometry increases in both the biometric and the forensic fields, it is important that we have a full understanding of relationships and possible inferences that can be made regarding other aspects of the human form.

Acknowledgements

<Anonymous>

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<Anonymous Publication>

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Highlights

- A novel dataset to explore linkages between hand, stature, leg and stride measures.
- The use of an automated system for the measurement of anatomical lengths.
- We show the ability to predictively model relationships between measures.
- We indicate the possibility of calculating or checking relationships for forensic use.