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# Preliminary Anthropometric Specification for Land Vehicles

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## **ABSTRACT**

The Australian Defence Force (ADF) will be acquiring a number of new vehicles in the near future. When acquiring a new vehicle numerous factors must be considered when determining the most suitable option for the ADF. One very important consideration is the human machine interface. Using the anthropometric data gathered on male personnel based at Robertson Barracks, Darwin, in 2010 an anthropometric specification which describes the “hard to fit” members of the Army population has been developed. This specification can be used to inform the acquisition of new vehicles or the upgrading of existing vehicles.

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# Preliminary Anthropometric Specification for Land Vehicles

## Executive Summary

A number of new land vehicles will be acquired by the Australian Army in the coming years. When acquiring a new vehicle numerous factors must be considered when determining the most suitable option for the Australian Defence Force (ADF). One very important consideration concerns the anthropometric accommodation aspect of the human machine interface. Ideally, the vehicle should safely accommodate a wide range of male and female body sizes.

The most recent anthropometric survey of the Australian Army population was conducted in 2010 at Robertson Barracks in Darwin. The survey, conducted by the University of South Australia, measured 371 male and 46 female personnel ranging in age from 18 to 53 years old. The subjects came from a broad range of corps, including infantry, engineering, signals and artillery. In total, 40 manual measurements were taken on each subject, including measurements relevant to protective equipment, clothing and seated workstations, such as sitting height, buttock-knee length and chest circumference. In addition, each subject was laser scanned in two standing postures using a Vitus XXL laser scanner. Using the male data (as only 46 females were surveyed only the male data was used for this analysis) and a statistical technique called principle component analysis an anthropometric specification was developed which describes the “hard to fit” members of the male sample. The “hard to fit” personnel are not only the tall and the short, but subjects of average height who have contrasting proportions, a long torso and short limbs, for example. This specification can be used to inform the anthropometric fit aspects of new vehicle acquisitions and any upgrades of existing vehicles. It is recommended that when sufficient data for Army females becomes available this specification be updated to incorporate females.

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## Glossary

ADF	Australian Defence Force
CAD	Computer Aided Design
MAM	Multivariate Accommodation Model
MOD	Ministry of Defence
PC	Principal Component
PCA	Principal Component Analysis
UK	United Kingdom
USAF	United States Air Force

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# 1. Introduction

The Australian Defence Force (ADF) will be acquiring a number of new land vehicle types in the near future. When acquiring a new vehicle, numerous factors must be considered when determining the most suitable option for the ADF. One very important consideration concerns the anthropometric accommodation aspects of the human machine interface. Ideally, the vehicle should safely accommodate (both as operator and passenger) a large proportion of ADF personnel.

Historically, when designing a seated work environment, like a vehicle workstation, it has been assumed that the difficult to accommodate subjects are the uniformly very small and the very large. When specifying the proportion of the population to be accommodated a percentile method has been traditionally used (a percentile gives the relative ranking of a measurement). For example, if 90% of males were to be accommodated in a vehicle, it was assumed that by specifying the 5<sup>th</sup> to 95<sup>th</sup> percentile male size values for key cockpit dimensions (such as buttock-knee length and sitting height) when designing a vehicle, then approximately 90% of the male population would be accommodated. Unfortunately, due to the multivariate nature of human anthropometric dimensions (for example, a person may have long limbs and a short torso), a much smaller percentage of people are actually accommodated than the uniform model predicts (Robinette and McConville 1982). Furthermore, as the number of anthropometric restrictions increases, the proportion of the intended population accommodated decreases.

To illustrate the potential problems that can occur due to using a percentile specification, an example from the United States Air Force (USAF) is presented here. The T-1 Jayhawk is a twin engine jet aircraft that is used by USAF to train pilots who will go on to fly tanker and transport aircraft. The initial percentile anthropometric specification required the aircraft to accommodate (ensuring the pilot has the required field of view, has the appropriate clearance with the cockpit structures, and can reach all the controls) 98% of the pilot population (Zehner and Hudson 2002). However, an “in cockpit” assessment of the anthropometric accommodation of this aircraft found that it did not accommodate 30% of Caucasian pilots, 80% of African American pilots and 90% of female pilots for whom it was designed (Robinette, Nemeth et al. 1998). The pilots who were eliminated typically had a small seated eye height and long legs, or a short seated height and a large thigh circumference. The pilots with a short seated height were required to have the seat at or near its highest position, which then made it difficult to achieve full control yoke range of motion.

Following the identification of the problems inherent in the percentile method, a specification technique based principal component analysis (PCA) was developed. PCA is a data reduction technique that minimises the number of dimensions needed to describe anthropometric variability by combining related measurements into a set of factors based on their correlation (Zehner, Meindl et al. 1993). Typically, in cockpit accommodation studies the first two factors are retained for the analysis, with these components accounting for approximately 90% of the original variation. About eight to ten test cases (virtual people) are then identified that represent the extreme cases from the population of interest. These cases represent the very tall and very small subjects, along with subjects of near average height who have contrasting

proportions (for example, a long torso and short limbs). It should be noted that while these test cases describe the extremes of the population for vehicle accommodation they do not necessarily describe extremes of the population for other applications, for example, the design of a helmet. In this case, a separate analysis would have to be conducted using the key dimensions that define helmet fit. The PCA technique has been applied to a wide range of workstation and protective equipment design problems, including aircraft cockpits (Zehner, Meindl et al. 1993), office workstations (Gordon 2002), tractor cabs (Hsiao, Whitestone et al. 2005), fall protection harnesses (Hsiao, Bradtmiller et al. 2003), and body armour (Gordon, Corner et al. 1997).

The purpose of this report is to provide an anthropometric specification using the PCA/extreme cases technique and the male data from the most recent Australian Army anthropometric survey. This specification can be used to inform and evaluate the anthropometric accommodation aspects of new land vehicles as well as any proposed upgrades of existing land vehicles.

## 2. Method

### 2.1 Anthropometric Data

The most recent survey of ADF Army personnel was conducted from 21 June to 2 July 2010 at Robertson Barracks, Darwin. In total, 371 males and 46 females aged 18 to 53 years old were surveyed by a team from the University of South Australia<sup>1</sup> (Tomkinson and Dale 2010). The measurement team were qualified at a minimum level two by the International Society for the Advancement of Kinanthropometry. Furthermore, the measurement team had completed a 20 hour training course on the survey measurements. The survey subjects came from a broad range of Army occupations, including infantry, engineering, signals and artillery. A total of 40 manual measurements were taken on each subject, including measurements relevant to protective equipment, clothing and seated workstations, such as sitting height, thumb tip reach, buttock-knee length, and chest circumference [see Tomkinson, Dale, et al (2010) for a description of all the measurements; see Furnell (2011) for summary statistics]. In addition to the manual measurements, each subject was also laser scanned using a three-dimensional Vitus XXL laser scanner (see Figure 1) in two standing postures (see Figure 2 and Figure 3) to enable additional measurements to be extracted from the scans at a later date. In total, it took about 45 to 60 minutes to process each volunteer. Initially, each subject completed a brief demographic questionnaire. Following this, the subject then changed into form-fitting underwear and forty manual measurements were then taken on each subject. After this, a number of small landmarks were then placed on 16 body landmarks, including acromion (left and right) and cervicale. These landmarks were placed on the body as these landmarks could not be accurately located by looking at the scan. The subject then put on a rubber swimming cap so the shape of the head could be captured in the scan. After this, the subject then stood in the centre of the scanning station and two scans were taken. Using specialist software, numerous body dimensions could then be extracted from these body scans (see

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<sup>1</sup> One team member was from the Australian Institute of Sport.

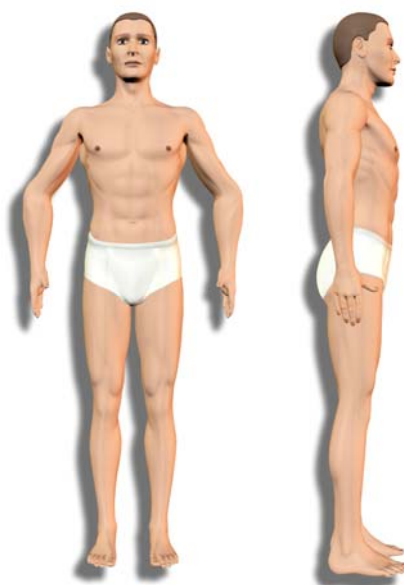
Figure 4 for an example). Given only 46 females were measured, only the male data will be used for this analysis. Summary statistics for males for key dimensions relevant to seated workstations are listed in Table 1.



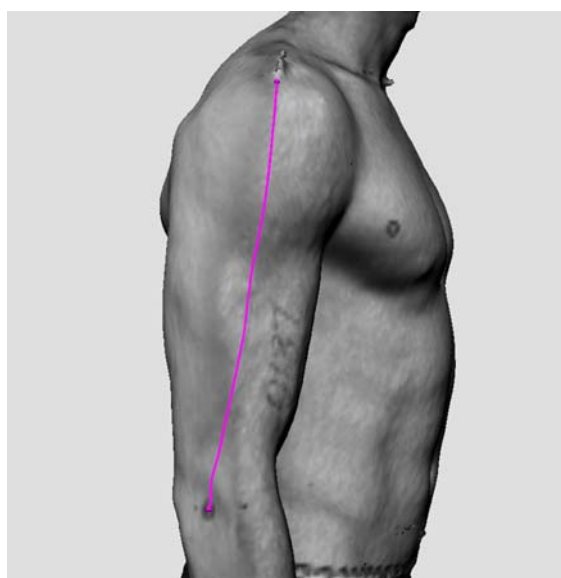
*Figure 1 Subject in the scanning unit*



*Figure 2 Scanning posture one*



*Figure 3 Scanning posture two*



*Figure 4 Measurement of acromion-radiale length using Cysize*

*Table 1 Summary statistics for some key vehicle dimensions for males. All units are millimetres.*

Measurement	Mean	5 <sup>th</sup> Percentile	95 <sup>th</sup> Percentile
Sitting height	931	879	985
Eye height, sitting	807	747	866
Thumb-tip reach	786	716	860
Acromion height, sitting	602	553	655
Buttock-knee length	616	570	664
Knee height, sitting	553	505	598
Buttock-popliteal length	501	458	545
Popliteal height	438	397	479
Bideltoid breadth	493	448	540
Hip breadth, sitting	371	326	428

## 2.2 Statistical Analysis

Following the approach of Zehner, Meindl et al. (1993), the multivariate accommodation model<sup>2</sup> (MAM) version 3 and the most recent male Army survey data was used to create eight boundary cases that enclose 90% of the survey subjects. These boundary cases were supplemented with minimum and maximum values for critical clearance dimensions.

## 3. Results

A principal component analysis was conducted using the MAM on the male subjects. Following this, key anthropometric cases were identified that described the extremes of the male population. The results of this analysis, along with summary statistics for the clearance dimensions are presented below.

The first two principal components were retained for this analysis. The first principal component describes the overall size of the subjects, while the second component, on the other hand, describes the contrasting height of the torso and the length of the limbs. A plot of the values of each of the male subjects for the first two principal components is shown in Figure 5. Also plotted on this figure is an ellipse that encloses 90% of the male cases. Following Zehner, Meindl et al. (1993), eight points (A – D, W – Z)<sup>3</sup> are selected on the ellipse at the intersection of the ellipse and the axes and at the mid-points between the axes to represent the extreme cases of the population for this particular application (setting the accommodation level at 90%). The anthropometric dimensions of these eight cases are listed in Table 2. The horizontal axis shown in Figure 5 represents the overall body size of the subjects, whilst the vertical axis represents the contrasting proportions of the subjects. Case W represents the overall largest subject, while case Y represents the overall smallest subject. Cases X and Z represent subjects

<sup>2</sup> The MAM software was kindly supplied by Dr Greg Zehner (Senior Research Physical Anthropologist, Air Force Research Laboratory, Wright-Patterson Air Force Base, USA).

<sup>3</sup> Each case can be thought of as a virtual person of a particular size and proportion.

of approximately average height who have contrasting proportions. Case Z has a long torso (large sitting height) and relatively short arms and legs. In contrast, case X has a small sitting height and relatively long arms and legs. Cases B (long limbs, short torso) and D (long torso, short limbs) are below average height, although not as short as case Y, and like cases X and Z have contrasting proportions. Finally, cases A (long limbs, short torso) and C (long torso, short limbs) represent subjects that are tall, but not quite as tall as case W, who have contrasting proportions.

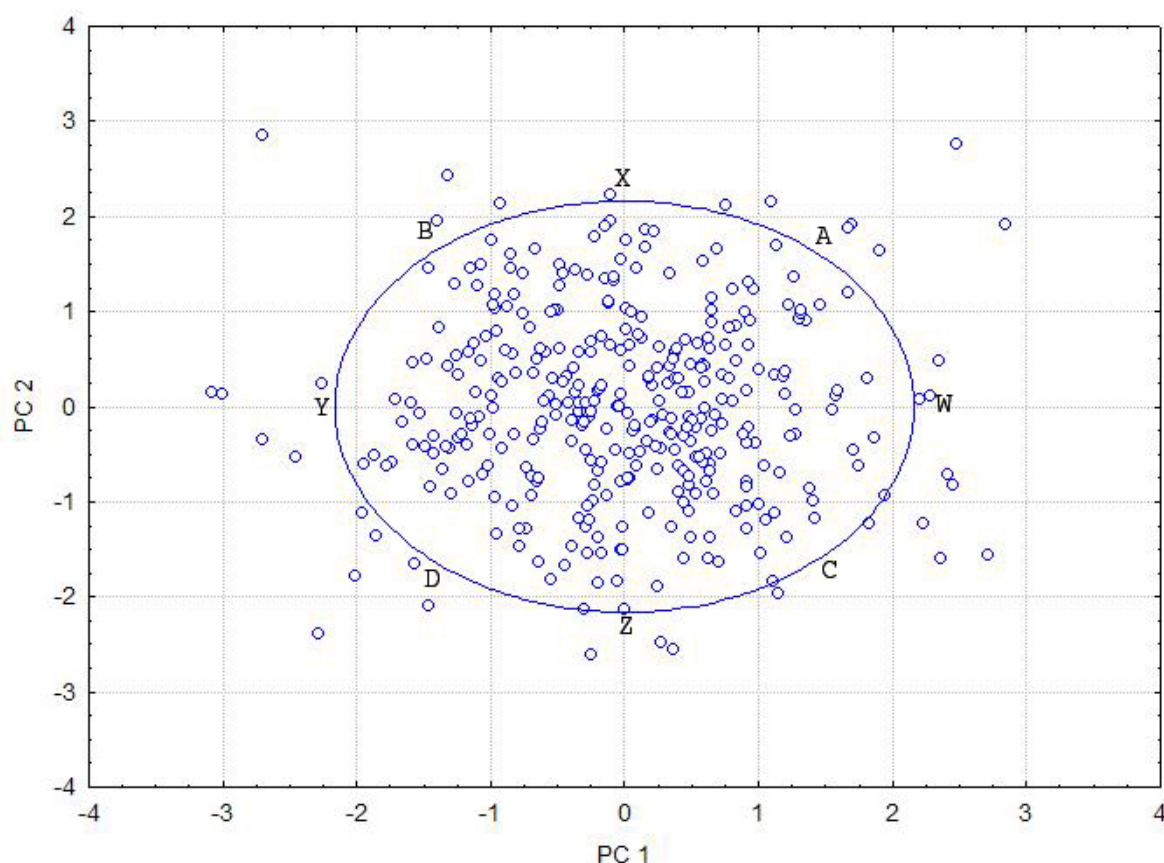


Figure 5 Scatterplot of the male cases for the first two principal components. Also plotted is an ellipse enclosing 90% of cases, along with eight boundary cases (A-D, W-Z).

### 3.1 Boundary Cases

Table 2 Eight boundary cases for the male dataset (90% accommodation). All units are millimetres.

Measurement	Case A	Case B	Case C	Case D	Case W	Case X	Case Y	Case Z
Buttock-knee length	671	600	633	562	667	643	566	590
Thumbtip Reach	958	868	995	905	856	825	716	746
Eye height, sitting	829	737	876	784	872	773	741	840
Knee height, sitting	609	538	568	497	603	582	503	524
Acromion height, sitting	619	543	661	586	656	572	549	632
Sitting height	958	868	995	905	995	905	868	958



### 3.2 Clearance Dimensions

Some anthropometric dimensions that are important for vehicle accommodation are simply clearance dimensions and can be considered in isolation (Zehner, Meindl et al. 1993). For example, anthropometric dimensions like hip breadth, sitting; buttock-popliteal length; and popliteal height are important when assessing if the dimensions of the seat are appropriate. Also, extreme values of shoulder width must be considered when assessing the clearance of the person with the vehicle structures. Summary statistics for the key anthropometric clearance dimensions are presented in Table 3.

*Table 3 Male clearance dimensions for vehicle accommodation. All units are millimetres.*

Dimension	Minimum	Maximum
Buttock-popliteal length	432	586
Popliteal height	361	519
Bideltoid breadth	405	595
Hip breadth, sitting	299	520
Abdominal extension depth, sitting	177	377
Forearm-forearm breadth	416	692
Elbow rest height	161	310
Thigh clearance	119	214
Foot length	233	316
Foot breadth	86	117
Hand breadth	78	102

## 4. Discussion

Using the male data from the most recent survey of Army personnel and the anthropometric accommodation methodology developed by Zehner, Meindl et al (1993), eight male boundary cases that encompassed 90% of the male population were created. These boundary cases ranged from the very small subject (case Y), who has a buttock-knee length of 566 mm and a sitting height of 868 mm to the very big (case W) who has a sitting height of 995 mm and a buttock-knee length of 667 mm. The remaining six cases represent subjects who have heights between cases Y and W but who have contrasting proportions. Cases D, Z and C represent subjects who have a long torso and short limbs, while cases B, X and A represent subjects who have long limbs and a short torso. These eight cases range in height from approximately 1690 mm to 1919 mm tall (based on the average height of the three nearest neighbours to cases Y and case W) and represent the boundary envelope which describes 90% of the male Army population. Supplementing these boundary cases, summary statistics for anthropometric clearance dimensions (see Table 2 and Table 3), such as buttock-popliteal length, were also calculated, to ensure, for example, the dimensions of the seat are appropriate. Together, Table 2 and Table 3 form a specification which describes an accommodation envelope that encloses 90% of male personnel.

## 4.1 Accommodation Assessment Options

Having created an anthropometric specification, there are two main options for the ergonomic assessment of the vehicle. Firstly, an “in vehicle” assessment can be conducted using “live” test subjects in the vehicle, or a mock up of the proposed vehicle. Secondly, a virtual assessment can be conducted using a computer aided design (CAD) model of the vehicle and human modelling software such as Jack. The relative merits of each approach are discussed below.

### 4.1.1 In Vehicle Assessment

Traditionally, in the early stages of a vehicle development a mock up of the vehicle is constructed and the design would be assessed using, typically, a combination of anthropometric manikins and “live” test subjects. If any problems are encountered with the design alterations are made to the mock up, or a completely new mock up would be constructed. Following this, one or more prototype vehicles may be constructed before the design would be finalised, again with the design, typically, assessed using a combination of manikins and human subjects. A key advantage of using human subjects in the ergonomic assessment of a vehicle design is that a full range of tasks, such as vehicle ingress/egress, and reach to controls can be assessed in a realistic fashion using the mock up or vehicle. Furthermore, the impact of the clothing and protective equipment worn by the operator on the clearance with the vehicle structures and the operator’s position, posture and reach to controls can be easily and accurately assessed. In addition, if vehicle operators are used for the assessment, valuable information on operational issues can be gathered during the assessment. While in vehicle assessment offer many benefits, access to the vehicle or mock up for a sufficient time to conduct the assessment can be problematic. It can also be difficult to co-ordinate test subjects that reflect the anthropometric extremes of the intended user population (typically about 30 subjects are used in cockpit accommodation studies).

### 4.1.2 Human Modelling Assessment

A key advantage of the human modelling approach is that any ergonomic issues associated with a vehicle design can be identified early in the design cycle, before the first mock up has been constructed. Furthermore, manikins can be created that represent the extremes of the population, enabling the accommodation of the vehicle to be assessed in a systematic fashion with any ergonomic issues, such as lack of clearance with the vehicle structures, identified and visually demonstrated in a compelling fashion. Furthermore, potential solutions to any issues can be identified and trialled in a timely and cost effective way. While there are some significant advantages to a virtual ergonomic assessment, especially early in the design life cycle, the virtual approach also has a number of potential shortcomings. For example, as the digital models typically model the human as an incompressible object, care must be taken positioning the manikin in the seat to ensure realistic postures and positions are modelled. Also, given the limitations of the models kinematics, they are typically best suited to static assessments of reach and clearance, with the assessment of dynamic tasks such as egress best suited to real people. Another limitation of the human modelling approach is modelling of the clothing and equipment worn by the operator and the impact of these items on the dimensions of the manikin, the manikin’s posture and position. Currently, there is no

comprehensive set of clothing or protective equipment correction factors available for the clothing and protective equipment worn by ADF personnel (Davis and Furnell 2011). As a guide to the change in dimensions caused by the clothing and protective equipment, Appendix A lists correction factors used by the United Kingdom Ministry of Defence, along with some data for ADF protective equipment.

#### 4.1.3 Summary

In summary, the use human modelling tools in the assessment of vehicles offer a number advantages, especially when used early in the design process, before the first mock up has been constructed. Although the human modelling software can be used throughout the design and acquisition process, its maximum value is derived from being used early in the development of the vehicle as part of an iterative process that may commence with the virtual analysis of the proposed vehicle, and proceed to the assessment of physical mock ups then to vehicle prototypes. Use of human modelling software as part of a systematically structured process of analysis ensures that risk associated with incorrectly designed workspaces can be ameliorated progressively.

## 5. Recommendations

1. It is recommended that Table 2 and Table 3 be used as an anthropometric specification for the acquisition and upgrading of land vehicles.
2. It is recommended that this specification be reviewed when further data on the male Army population becomes available.
3. It is recommended that this specification be updated when sufficient data becomes available for the female Army population.
4. It is recommended that the intergenerational change in the size and shape of Army personnel be investigated so that future specifications can incorporate these predicted changes to maximise accommodation throughout the vehicle's life.
5. It is recommended that a library of computer aided design models of protective equipment and other items worn or carried by vehicle occupants be established to assist in virtual vehicle evaluations. It is also recommended that a study to determine clothing and protective equipment corrections be conducted.

## 6. Concluding Remarks

The Australian Defence Force will be acquiring a number of new vehicles in the near future. When acquiring a new vehicle numerous factors must be considered when determining the most suitable option for the ADF. One very important consideration is the human machine interface. The vehicle should be designed to ensure a wide range of personnel can position the seat so that they have an appropriate internal and external field of view, can reach all the controls, and maintain a safe clearance of the vehicle structures. Using the anthropometric data gathered on male personnel based at Robertson Barracks, Darwin, in 2010 an anthropometric specification which describes the "hard to fit" members of the Army population has been developed. This specification can be used to inform the acquisition of new vehicles or the upgrading of existing vehicles.

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## Appendix A: Clothing and Equipment Correction Factors

Currently, there is only limited data available for ADF specific clothing and equipment correction factors. Table 4 (right hand data column) lists the dimensional correction factors available for personnel wearing ADF standard body armour (chest depth and abdominal depth only). The left hand data column lists the dimensional correction factors from the United Kingdom (UK) Ministry of Defence (MOD 2008) for standard combat clothing and equipment worn by UK personnel, while the middle data column lists the correction factors for cold weather clothing and equipment worn by UK personnel. This data can be used as a guide for the increase in body dimensions that should be considered when assessing or developing a workstation.

*Table 4 Clothing and equipment correction factors (all units are millimetres)*

<b>Dimension</b>	<b>UK Combat</b>	<b>UK Cold Weather</b>	<b>ADF Body Armour</b>
Stature	64	76	N/A
Eye height, standing	27	36	N/A
Sitting height	38	51	N/A
Eye height sitting	1	10	N/A
Thigh clearance	4	23	N/A
Knee height	33	56	N/A
Buttock-knee length	5	51	N/A
Shoulder breadth	6	152	N/A
Hip breadth	13	152	N/A
Abdominal depth	13	51	N/A
Foot length	41	68	N/A
Foot breadth	5	46	N/A
Hand breadth	N/A	43	N/A
Hand thickness	N/A	84	N/A
Chest depth	N/A	N/A	74
Abdominal depth	N/A	N/A	88

N/A – data not available

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