3D Body Scanning Method for Close- Fitting Garments in Sport and Medical Applications

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Abstract

Close-fitting pressure garments and compression therapy are widely used these days for both sport and medical applications. The degree of pressure produced by a close-fitting compression garment is determined by a complex interrelation between the following principle factors: the construction and fit of the garment, structure and physical properties of its materials, the size and shape of the part of the body to which it is applied and the nature of the sporting or everyday activity undertaken. The negative fit of such garments is of the utmost importance to ensure the correct amount of pressure is generated by them. This research addresses the Development of a Lower Body Measurement Method as applicable to close-fitting garments for sport and medical applications. [TC]² NX-16 3-Dimensional Body Scanner is used for scanning and generation of the true to scale body model with modifications to the Measurement Extraction Profile made to facilitate the body measurement at points of critical importance for the required application. Customised measurements are then extracted and used for the evaluation of the garment performance or garment engineering.
The developed method is validated on a representative sample of human subjects both male and female

Keywords: 3d body scanning, sport garment, compression garment

1. Introduction

Compression garment technology has been used for more than 50 years in compression hosiery for treatment of chronic venous insufficiency. Athletes also have experimented for years with compression garments in sports both as an ergogenic, performance enhancement and recovery aid. The degree of pressure produced by a close-fitting compression garment is determined by a complex interrelation between the following principle factors: the construction and fit of the garment, structure and physical properties of its materials, the size and shape of the part of the body to which it is applied and the nature of the sporting or everyday activity undertaken [1].
With the material elastic properties and the garment construction being constant, the change in the size and shape of the body parts to which garment is applied becomes critical in terms of change of the amount of pressure generated.
The critical points for the body and pressure measurements in sport apparel applications are currently not defined in the research literature. There is some reference literature used by sport brands to identify the critical pressure measuring points for lower body compression garments that are not supported by credible research. Lawrence and Kakkar [2] concluded that an optimal pressure gradient of 18mmHg at the ankle, 14 mmHg at the calf, 8 mmHg at the knee, 10 mmHg at the lower thigh and 8 mmHg at the upper thigh would generate the fastest venous flow which will lead to the enhanced physiological characteristics critical to human performance. Some research into sports compression garments refers to measurements of pressure being taken at ankle, calf and lower and upper thigh [3]. However the exact position of these points varies between research investigations: some define ankle as the widest girth at ankle, some as the minimum girth at ankle and some as “just above the ankle”.
The use of medical compression hosiery is a much better researched area, and a number of relevant standards exist for the testing and classification of these medical hosiery compression garments [4,5] with a much more defined position for the *in vitro* pressure measuring points during garment testing and the attribution of the pressure class to the garment (e.g. Class I, Class II etc.). The points of measurement of pressure generated by medical compression garments *in vivo* are defined in [6] and are: ankle at point of minimum girth, area at which the Achilles tendon changes into the calf muscles (~10~15cm proximal to the medial malleous), calf at its maximum girth, just below the tibial tuberosity, centre of patella and over the back of the knee, mid-thigh between patella and groin, 5 cm below the centre point of the crotch, greatest lateral trochanteric projections of the buttock and centre point of the crotch.

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Both lower body sport compression garment manufacturers and medical hosiery manufacturers adopted the hosiery sizing that utilizes the relationship between the height and weight or hip girth and weight values for a human body [7,8]. However most manufacturers have developed their own in-house size chart designs that are based on the body weight/height principles but do not follow standard size grids to the letter with substantially increased weight and height range covered [9,10,11]. Some incorporated a very basic body shape categories for women's garments, such as "A"-shaped and "H"-shaped into their sizing system [9]. There are more measurements incorporated into the sizing charts for the medical compression hosiery such as narrowest girth at the ankle, widest girth at the calf, at thigh (approximately 5 cm from the groin [11], however the defining measurement for the selection of the appropriate garment size for the required compression class is the narrowest girth at the ankle.
A number of existing research investigations were directed to the development of the body group classifications such as "hourglass", "oval", "triangle" etc. [12,13]. In these studies each category is given ranges of numerical values that correspond to the body measurements that are significant for that shape, e.g. in study [12] the "bust", "waist", "hip", stomach', and "abdomen" circumferences were used in combination to define each shape. It is clear that in these studies the defining measurements are focused mainly on a trunk area of the human body and not on a lower body. In addition these classifications are directed to the general population and while they could be applicable to this general population may be of little relevance to the sport and fitness participants.
In elite sport the physical, physiological, tactical and technical requirements of the sport are paramount to success of the athlete. Their physique, body type, proportionality or body lever lengths are capacities that are often critical for selection of an athlete for a particular sport. For example, the composite shape of the athlete is a consideration in sports in which overcoming or even promoting aerodynamic drag is vital. Cycling, speed skating and ski jumping, for example, are substantially affected by the resultant shape that the athlete can make with his or her body. In performance sport, a morphological optimization process is used by which the ideal body size and shape for a particular sport are selected or modified [14]. It is also determined by the existing research that the body size of the athletes is different from that of the source population. For example, high-level male and female athletes are generally higher in the mesomorphic sector of the somatochart [15] when compared to individuals from the general population [14], who are generally more endomorphic as well as more randomly spread around the somatochart, where somatotype is a quantified expression or description of the present morphological conformation of a person [16]. There is also a very distinctive difference in mean somatotypes of the athletes participating in different competitive sports and thus there is also a distinctive difference in their lower limbs size (length and girth distribution) [17]. For example, this difference between triathlon and soccer athletes is reflected in mean somatotypes of 1.7-4.3-3.1 for thriathletes and 2.6-5.5-1.9 for soccer players.
As the compression sport garments are worn by performance athletes as well as fitness enthusiasts and medical hosiery is worn across general population and as the amount of pressure generated by these garments depends on their size and fit it is important to develop a protocol for measuring the wearers lower body size for the appropriate size selection and possibly for the custom engineering of such garments. Thus the quantification of human morphology is a fundamental requirement for this purpose. All dimensions of a human body are normally defined relative to landmarks. Landmarks are usually identified by palpation and marked with a fine-to-medium point non-permanent pen or pencil [18].
Three-dimensional body scanning technology used to capture anthropometric measurements is now becoming a common research, design and engineering tool in the apparel field. The efficiency of 3D body scanning, from which an infinite number of measurements and relating data can be obtained, is well known. However the previous research on body measurements using 3D body scanners has mostly been focused on the investigation of apparel and apparel ensembles with a positive fit and on the area of population surveys in various sizing studies [19,20,21].
This research addresses the development of a lower body measurement method as applicable to lower body close-fitting garments for sport and medical applications.

2. Methodology and Methods

The measurement points from existing research [4,5,6] were reviewed along with the requirements for evaluation of pressure generated by a lower body compression garments and the measuring methods both manual and utilizing 3D Body scanning were developed. Twelve human models were scanned according to the developed scanning method and protocol, and the acquired measurements analysed.

2.1. Manual Measurement Method

The developed body scanning method is based on the Manual Measurement Method developed and used earlier (Figure 1).

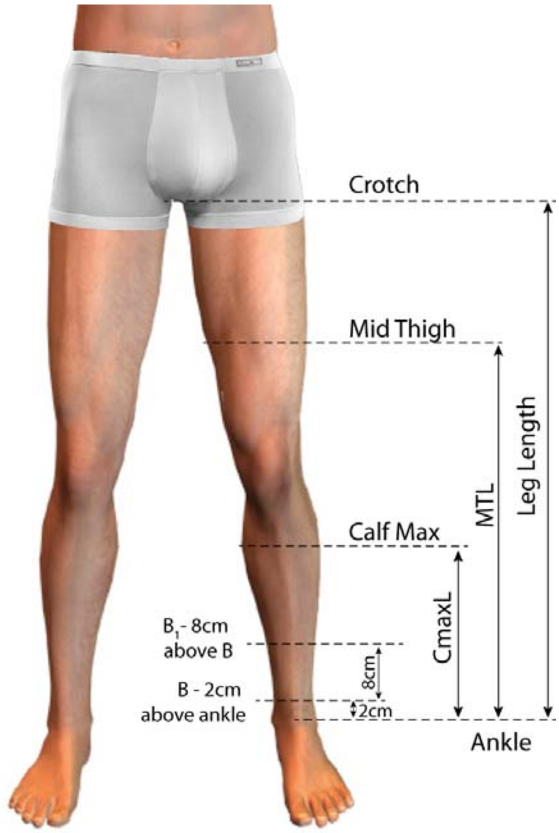


Fig. 1. Manual method and measuring points for lower body compression garments

The Measuring Protocol for the Manual Measuring Method includes the following steps with the subject standing straight with feet slightly apart: find and mark the ankle - the widest part at Medial Malleous, mark point B at 2cm above the ankle, mark point B1 at 8 cm above the point B, mark the Cmax at widest part of calf, Mark MT mid-thigh point, measure heights and girths of CMaxL, MTL and Leg Length in cm. The Manual Method is time-consuming, results only in few key measurements and relatively subjective.

2.2. 3D Body Scanning Method

NX-16 3-Dimensional Scanner is used for scanning and generation of true to scale body model [22]. The initial point cloud is acquired by the scanner and then is processed into 3D body model from which customised measurements can be extracted using the TC^2 body measurement software [22]. The Measurement Extraction Profile (MEP File) is modified according to the identified measurement points. A group of 7 male and 5 female healthy volunteers are selected in belonging to the range of sizes for a selected brand of compression sport apparel. The models are a typical cross-section of the brand's garment wearers ranging from size Small to Large, and size Extra Small to Medium for males and females respectively. The volunteers were informed about the experimental design and procedures. Approval from the RMIT University's Ethics Committee was obtained for the study.

The posture of each model is recorded with photographs at front and side views with the models wearing the sport compression tights and an own top. Models are directed to stand with feet at a specific distance apart marked on a mat, with hands in straight line apart from their body, the same position to that in which they are later scanned (Figure 2).

Fig. 2. Scanning position and posture form

Body mass and stature of the models are measured prior to the 3D Body Scanning. A calibrated scale is used and tare button is pressed prior to each measurement. Then a model is directed to stand in the centre of the platform with the mass being recorded to the nearest 0.01 kg. In the next step, Stature of models is recorded where the model is directed to stand erect with heels, buttocks and shoulders pressed against the vertical wall. The heels are touching and the arms are hung by the sides in a natural manner. Model is instructed “to look straight ahead and take a deep breath” and to gently but firmly stretch the vertebral column. The measurement is read from the measuring ruler attached to the wall and recorded.

Landmarks are put on specific points on each models body. Knee at the, Centre of Patella (Fig.3, b), is marked with a marker. The model is asked to bend his knee, where the patella is more recognizable by touch, and the centre of patella is marked using a marker.

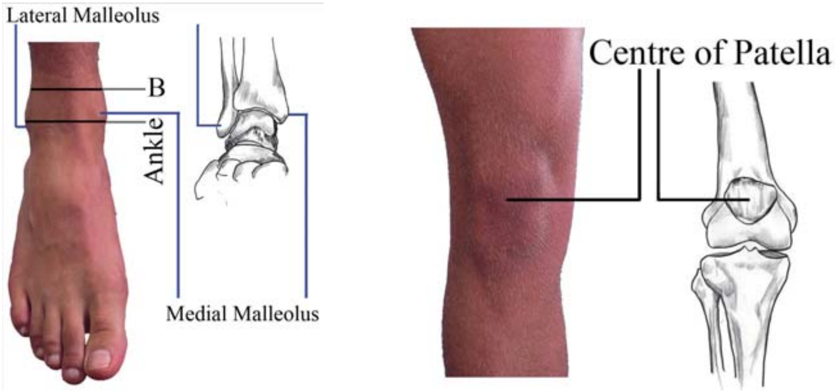
Body shape and size would influence the position of the top of the garment in the waist area. Hence the top front and back, and also the bottom edge of each garment are marked on the model’s body when the sport compression tight is worn. As the models scanned in their underwear with bare lower limbs, the specific recognisable scanning paper landmarks are placed on the marks at the points marked with a marker after removal of the tights and before the scanning process. Land marking sites are rechecked since the movement of the skin over the skeleton may alter the relative position of the mark when pressure is released.

2.3. Statistical analysis of data

An analysis on the validity and reproducibility of measurement results was performed. Two female models were scanned 30 times each. The variance in measurements at selected points was calculated, in order to estimate the required number of scans to ensure results within the specified tolerance of 0.3cm. It was determined that 6 scans were sufficient to generate measurements within acceptable tolerances. The mean value of the measurement at each point was used to construct the final measurement.

2.4. Measuring Points and Developed Measuring Protocol

Measuring points B, B1, C, D, F and G (Figure 5) are identified based on medical compression hosiery standards [4,5,6,23]. B is horizontal girth at 2 cm above the Ankle where Ankle is at average height between Lateral and Medial Malleolus (Figure 3,a), and B1, C, D, F and G are 8, 19, 27, 48 and 60 cm apart from point B, respectively. These distances are introduced according to sensor measuring points on Salzmann Compression Measurement Probe [24] for future possible validation.



(a) *(b)*

Fig.3. Right ankle: medial malleolus (a), and right knee, Apex of atella (b)

AMin is a minimum girth at the ankle, CMax (Calf) is the maximum girth between point B and the knee, K (Knee) is at centre of Patella (Figure 3, b), MT (Mid-thigh) is half way between the knee and the crotch point, and TMax (Max Thigh) is the maximum girth of the thigh. HDeep is the largest front to back depth between the crotch and W SB (waist small of back), HMax is maximum hip girth and Abd is the abdomen in reference to W SB.

The definition of the Knee is modified from the non-defined definition of this point within the TC^2 software.

There are two distinctive groups of measurements acquired by the developed protocol: measurements relevant to the both fit of the garment and pressure generated by it on lower limbs, and measurements relevant to the fit, positioning and comfort of the garment. The measurements B, B1, C, D, F and G belong to the first group and Cmax, MT, Tmax, Cmax, MT, Tmax, HDeep, Hmax, WG, W SB and Abd circumferential and height measurements belong to the second group.

The measuring protocol (Figure 5) consists of girth and length measurements of the lower limb and the lower trunk as established above.

The pre-defined points are edited after the 3D-scanning to match the landmarks such as the knee. The knee recognised by the 3D scanner is not specifically defined, and it is recognized as per each person's lower limb. The knee position is manually edited after the scanning process for each model to match the landmark placed on each model's leg prior to scanning. The points which identify the knee position are moved to match the landmark placed on Centre of Patella viewable on the scanning surface data (Figure 4). The landmark which is positioned at the bottom edge of the garment is used as a reference as to where the garment sits over the body. Also to recognize the exact garment waist on each model's body, the WG (waist of garment) is edited to the landmarks positioned on top front and back of the garment.

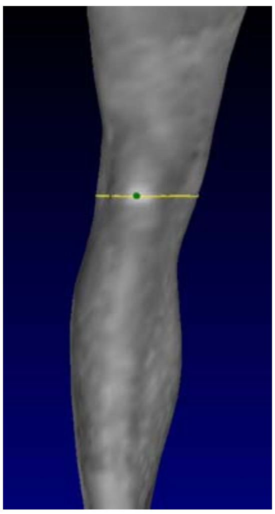


Fig.4. Knee edited to match landmark

Heights of all the circumferential measuring points from the floor are measured by the software. In order to determine the vertical distance between all the extra measuring points such as AMin L, CMax L, K L, MT L, and Tmax L and point B, ,the height of point B from the floor is subtracted from height of each point after all the measurements are extracted. The distance between the waist of the garment and the crotch (WGCr L) and the distance between the crotch and the B (Inseam–I) is extracted as well. These measurements provide the references to strain of the garment over the body in warp direction. Furthermore, heights Cr H, Hmax H and HDeep H to the floor are recorded.
The extra measurements would provide the additional detailed data of the overall measurement and size of the wearer. Also, they will be used in analysis of the garment construction, fit and sizing.

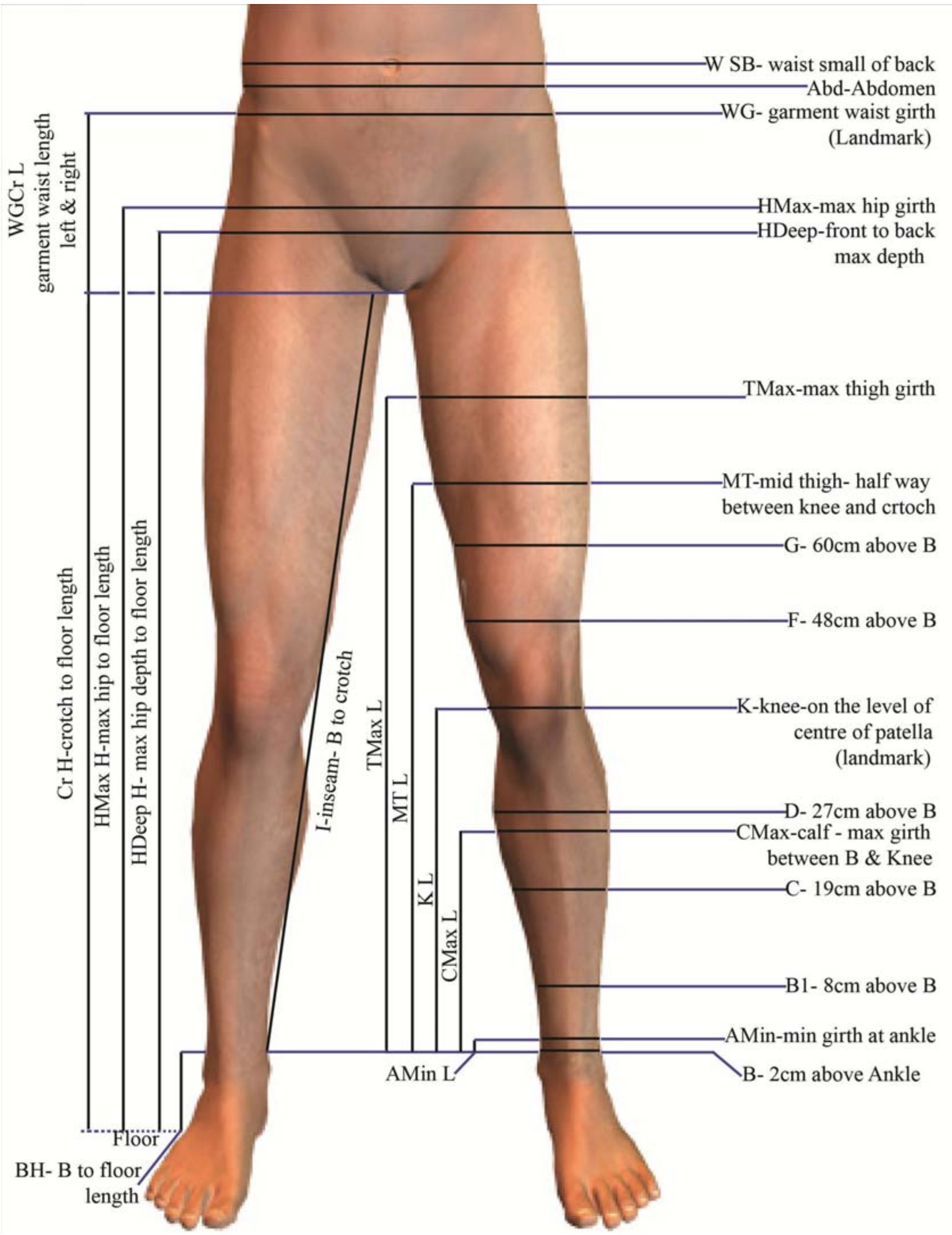


Fig. 5. Lower limb measuring points and measurements

3. Results

Table 1 provides some basic information on the models. The size of the garment is extracted from the sizing chart relative to the gender and garment -Tights and Shorts.

Table 1 Basic information on scanned models

Code	Garment size	Height	Weight	Code	Garment size	Height	Weight
Male		*Cm*	*kg*	*Female*		*Cm*	*kg*
M001 1055	S	180.0	70.5	W001 0952	S*	155.0	52.3
M002 1109	S*	170.0	66.6	W002 1004	S	171.5	58.8
M003 0300	M	176.0	88.4	W003 1026	S	160.5	56.8
M004 0309	L	181.5	101.1	W004 0117	XS**	158.0	49.8
M005 0324	MT	187.0	86.4	W005 0145	M	167.0	67.6
M006 0332	M**	180.0	76.5				
M007 1133	M	184.5	84.0				

*XS Worn

** S worn

As demonstrated in Figure 6, various body shapes and sizes belong to same sizing category.

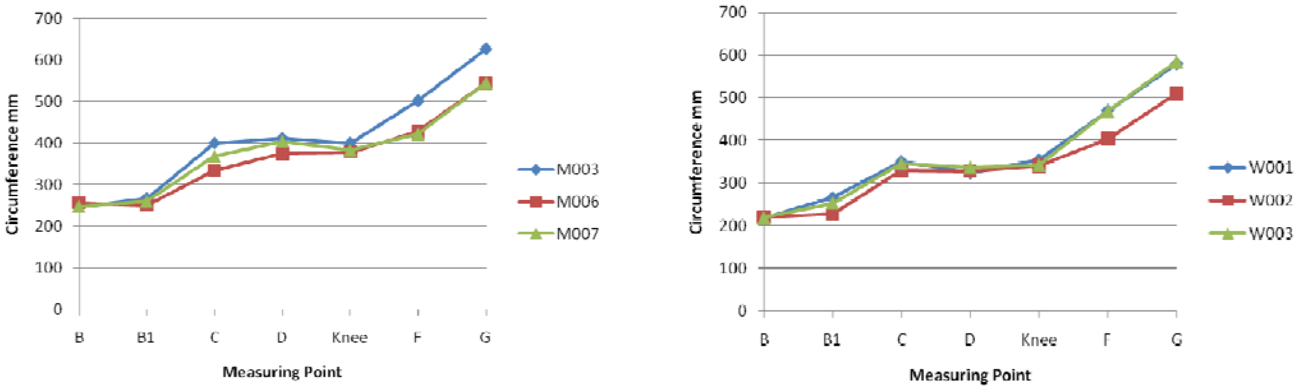
Figure 6 Posture photos of female models, W001, W002 and W003 – All Size S

Some of the measurements extracted during scanning of the human models are presented in Table 2.

Table 2 Extracted measurements of some of the Models belonging to same size category – Male and female

Model	Height	Weight	B	B1	C	D	F	G	Knee
	cm	*kg*	*mm*						
M003 0300	176.0	88.4	247.2	266.8	400.0	411.6	501.9	627.4	400.8
M006 0332	180.0	76.5	257.5	250.2	335.2	375.9	427.9	545.4	378.1
M007 1133	184.5	84.0	248.1	260.1	368.7	404.8	422.1	545.2	382.8
W001 0952	155.0	52.3	218.4	266.2	351.2	323.9	470.3	579.3	355.3
W002 1004	171.5	58.8	220.9	227.3	329.4	328.0	403.4	510.3	341.1
W003 1026	160.5	56.8	219.1	253.5	345.8	337.5	470.1	585.2	342.9

Lower body circumferences at critical measuring points B-G are plotted for above models (Table 2) who belong to the same size category (Fig.7a,b) and demonstrate the variation in their body measurements, for example 19% difference between the min and max girth at point C within the male models, and 17% difference between the min and max girth at point B1 amongst female models. These variations in the circumferences of lower limbs could potentially cause a considerable variation in pressure generated by compression garments. It is also interesting to note that the circumferences of the joint points not covered with muscle tissue are very close between models while the calf, thigh etc differ, in some cases significantly, between models - especially male.

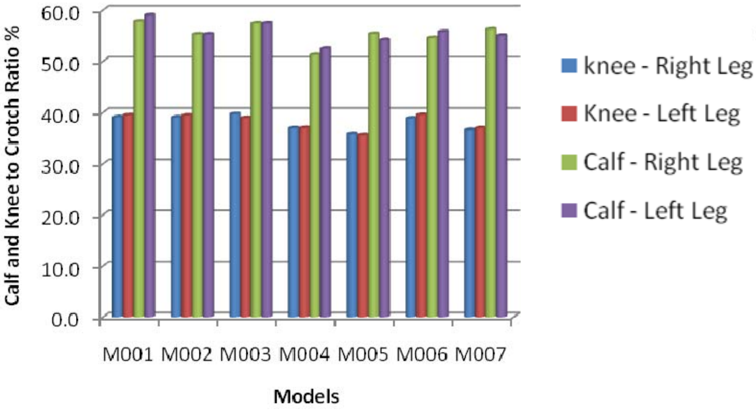


(a) (b)

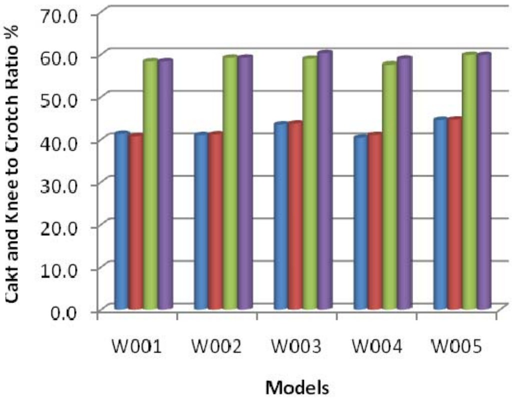
Figure 7 Circumference measurements at B-G on (a) male models in M and (b) female models in S

From the extracted measurements from 3D-Body Scanning, the position of main parts such as calf and knee are analysed amongst models (Figure 8).

It is clear from Figure 8 that the knee is positioned at average 38% with the range of 35-39% and calf at average of 55% with the range of 52-59% of crotch height amongst male models. As for female models, the knee is positioned at average 42.3% with the range of 40-45% and calf at average of 59% with the range of 58-60% of crotch height.



(a)



(b)

Figure 8 Calf and knee height to crotch height ratio (a) male models and (b) female models

It could be deduced that the calf and the knee are positioned proportionally higher in females in comparison to males, and thus the males would have longer thighs than females. It could also be concluded that the knee would not be positioned at exactly the middle of the garment length. This is an important fact by itself, and especially in combination with the fact of higher variation within the range of girths below the knee in males, for the garment design and engineering if the compression garment is to be constructed to induce a pre-determined pressure over a limb.

4. Conclusions

This research addressed the development of a Lower Body Measurement Method as applicable to close-fitting compression garments for sport and medical applications. The Developed Method and Protocol is based on [TC]² NX-16 3-Dimensional Body Scanner but can be used for other scanning software and generation of the true to scale body model. The body measurement at points of critical importance for the above application were carried out using the protocol and customised measurements are then extracted and will be used for the future evaluation of the garment performance or garment engineering.

Measuring points relevant to lower body compression garments are identified based on medical compression hosiery standards. The developed method is validated on a representative sample of human subjects both male and female and demonstrated the necessity of the particular protocol designed for the specific applications of close-fitting garments in sport and medical applications.

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