

Methodological article

3D body scanning method for close-fitting garments in sport and medical applications

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Abstract

Background: Close-fitting pressure garments and compression therapy are widely used for both sport and medical applications. These garments are constructed to have a negative fit where the size of the garment is smaller than the size of the body over which they are fitted. Due to this, these types of garments generate pressure on the underlying tissue of the human body. The degree and the distribution of the negative fit in such garments are of the utmost importance to ensure that the intended correct amount of pressure is generated by them. **Aim:** This research aims to develop a lower body 3D Body Scanning Measurement Method as applicable to garments with negative fit for sport and medical applications. **Methods:** New measuring methods both manual and with utilization of 3D Body scanning were developed with modifications to the Measurement Extraction Profile made to facilitate the body measurement at points of critical importance for the required application. Customised measurements were 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. **Results and Conclusions:** It is concluded that the Developed Method and 3D Scanning Protocol can be successfully used for lower body compression garments engineering and the calculation of the predictive pressure generated by these garments on the underlying human limbs. In addition, the protocol can be used for the generation of the true to scale body models and avatars.

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Background

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. These garments are constructed to have a negative fit, where the size of the garment is smaller than the size of the body over which they are fitted and thus they generate pressure on the underlying tissue of the human body. The degree of pressure produced 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 a 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. Lawrence and Kakkar [2] concluded that an optimal pressure gradient of 18 millimetres of mercury (mmHg) 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. A number of relevant standards exist for the testing and classification of medical hosiery compression garments [4,5], with a much more defined position for the *in vitro* pressure measuring points during garment testing. The points of measurement of pressure generated by medical compression garments *in vivo* are defined in Partsch et al. [6] and are: ankle at point of minimum girth, area at which the Achilles tendon changes into the calf muscles (~10~15centimetres (cm) proximal to the medial malleolus), 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.

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 are mainly focused on a trunk area of the human body and correspond to the body measurements significant for that shape, e.g. in a study conducted by Simmons et al. [12] the “bust”, “waist”, “hip”, “stomach”, and “abdomen” circumferences were used in combination to define each shape. In addition, these classifications are directed to the general population and, while they could be applicable to this general population, they 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 where morphological optimization process is used by which the ideal body size and shape for a particular sport are selected or modified [14]. 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].

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 [18].

Three dimensional body scanning technology used to capture anthropometric measurements is now becoming a common research, design and engineering tool. The majority of 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 also on the area of population surveys in various sizing studies [19,20,21]. This research aims to develop a lower body Manual and 3D Body Scanning Measurement Methods as applicable to garments with negative fit for sport and medical applications.

Method

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

Manual measurement method

The developed body scanning method is based on the Manual Measurement Method (Figure 1a). 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 (Calf)

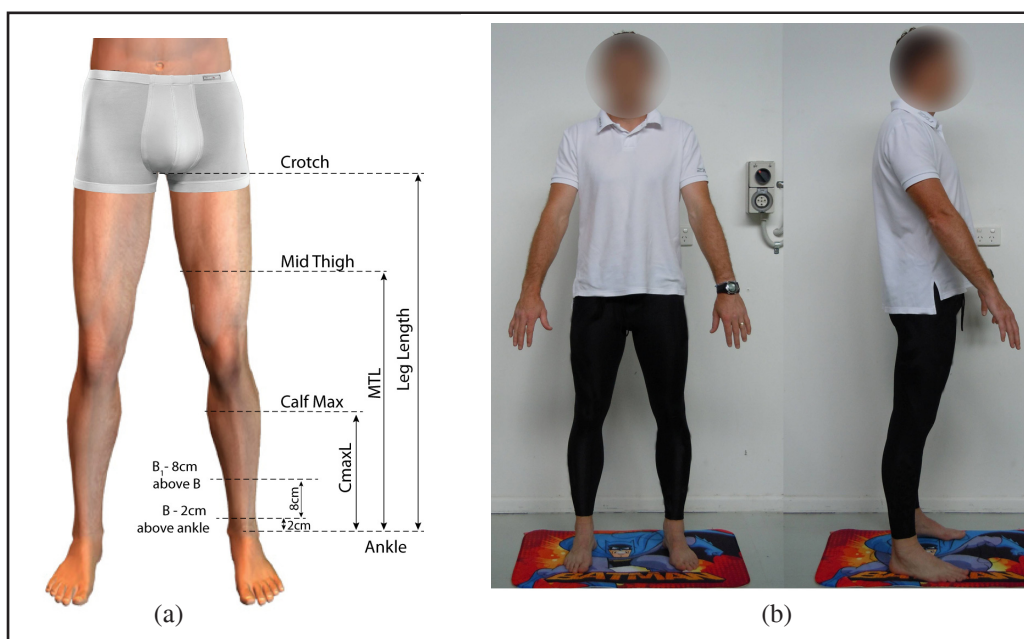


Figure 1. Manual method and measuring points (a) and Scanning position and posture form (b)

at widest part of calf, Mark mid-thigh (MT) 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.

3D body scanning method

NX-16 3D Body Scanner was used for scanning and generation of true to scale body model [22]. The initial point cloud was acquired by the scanner and then is processed into a 3D body model from which customised measurements can be extracted using the TC² body measurement software [22]. The Measurement Extraction Profile (MEP File) is modified according to the identified measurement points.

A group of seven male and five female healthy volunteers were selected in belonging to the range of sizes for a selected brand of compression sport apparel. The models were 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 (CHEAN B-2000385-08/10).

The posture of each model was recorded with photographs at front and side views with the models wearing the sport compression tights and their own top. Models were 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 1b).

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

Landmarks were placed on specific points on each model's body. Knee at the Centre of Patella (Figure 2b), was marked with a marker. The model was asked to bend the knee, where the patella is more recognizable by touch, and the centre of patella was 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 were marked on the model's body when the sport compression tight was worn. As the models scanned in their underwear with bare lower limbs, the specific recognisable scanning paper landmarks were placed on the marks at the points marked with a marker after removal of the tights and before the scanning process. Land marking sites were rechecked, since the movement of the skin over the skeleton may alter the relative position of the mark when pressure was released.

Statistical analysis of data

An analysis on the validity and reproducibility of measurement results was performed. Two female models were scanned 30 times each consequently. 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 0.3 cm. 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.

Measuring Points and Developed Measuring Protocol

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

Amin was the minimum girth at the ankle, CMax (Calf) was the maximum girth between point B and the knee, K (Knee) was at centre of the Patella (Figure 3b), MT (Mid-thigh) was

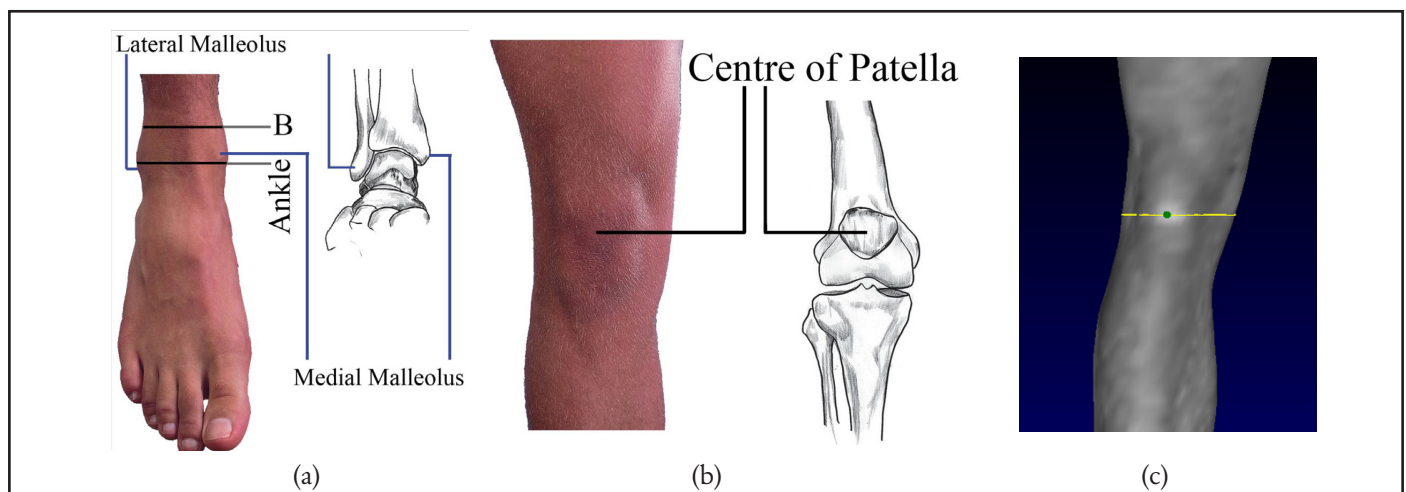


Figure 2. Right ankle: medial malleolus (a), right knee, Apex of atella (b) and Knee edited to match landmark (c)

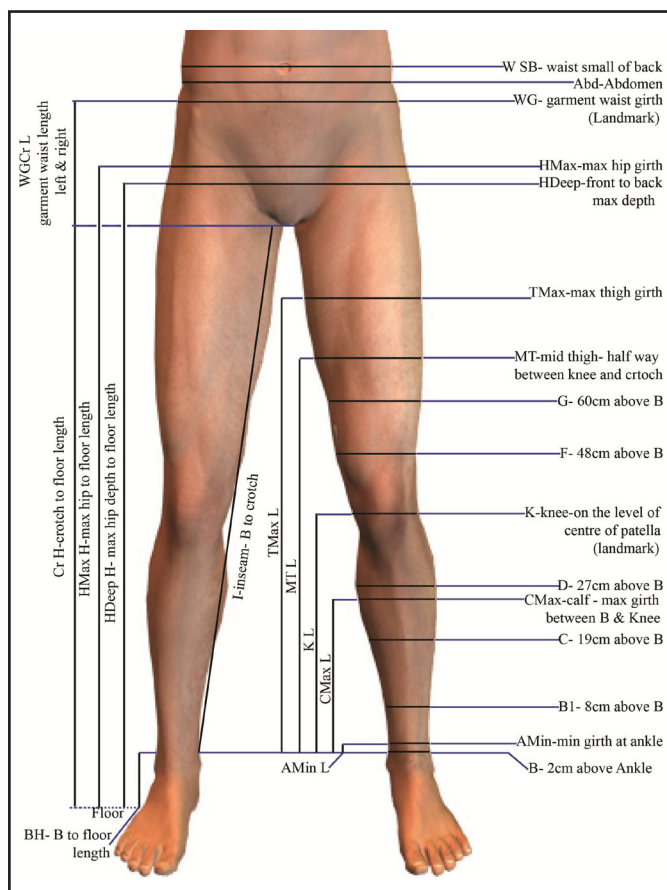


Figure 3. Lower limb measuring points and measurements

half way between the knee and the crotch point, and TMax (Max Thigh) was the maximum girth of the thigh. HDeep was the largest front to back depth between the crotch and the W SB (waist small of back), HMax was the maximum hip girth and Abd was the abdomen in reference to W SB. The definition of the Knee was modified from the non-defined definition of this point within the TC² software.

There were 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) consisted of girth and length measurements of the lower limb and the lower trunk as established above.

The pre-defined points were edited after the 3D scanning to match the landmarks, such as the knee. The knee recognised by the 3D scanner was not specifically defined, and it was recognized as per each person's lower limb. The knee position was 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 identified the knee position were moved to match the landmark placed on Centre of Patella viewable on the scanning surface data (Figure 3c). The landmark which is positioned at the bottom edge of the

garment was 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) was edited to the landmarks positioned on the top front and back of the garment.

Heights of all the circumferential measuring points from the floor were 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 was subtracted from the height of each point after all the measurements were 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) was extracted as well. These measurements provided the references to strain of the garment over the body in warp direction. Furthermore, heights Cr H (crotch), Hmax H (maximum hip length) and HDeep H (maximum hip depth) to the floor were recorded. The extra measurements provided the additional detailed data of the overall measurement and size of the wearer. Also, they were used in analysis of the garment construction, fit and sizing.

Results

The height of the male models ranged from 170.0cm to 187.0cm, with weight ranging from 66.6kg to 88.4kg. The height of the female models ranged from 155.0cm to 171.5cm, with weight ranging from 49.8kg to 67.6kg. The size of the garment was extracted from the sizing chart relative to the gender and garment -Tights and Shorts and ranged from S to L for men and from XS to M for women. As demonstrated in Figure 4, various models' body shapes and sizes belonged to same sizing category.

Lower body circumferences at critical measuring points B-G were plotted for the models who belonged to the same size category (Figure 5 a and b) and demonstrated the variation in their body measurements. For example, there was a 19% difference between the minimum and maximum girth at point C within the male models, and a 17% difference between the minimum and maximum 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 were very close between models, while the calf, thigh etc, differed, in some cases significantly, between models - especially for males.

From the extracted measurements from 3D Body Scanning, the position of main parts, such as calf and knee were analysed amongst models (Figure 6).

It was clear from Figure 6 that the knee was positioned at an average of 38%, with the range of 35-39% and the calf at an average of 55%, with the range of 52-59% of crotch height amongst male models. For female models, the knee was positioned at an average of 42.3%, with the range of 40-45% and the calf at an average of 59%, with the range of 58-60% of crotch height.

It could be deduced that the calf and the knee were positioned proportionally higher in females in comparison to males, and

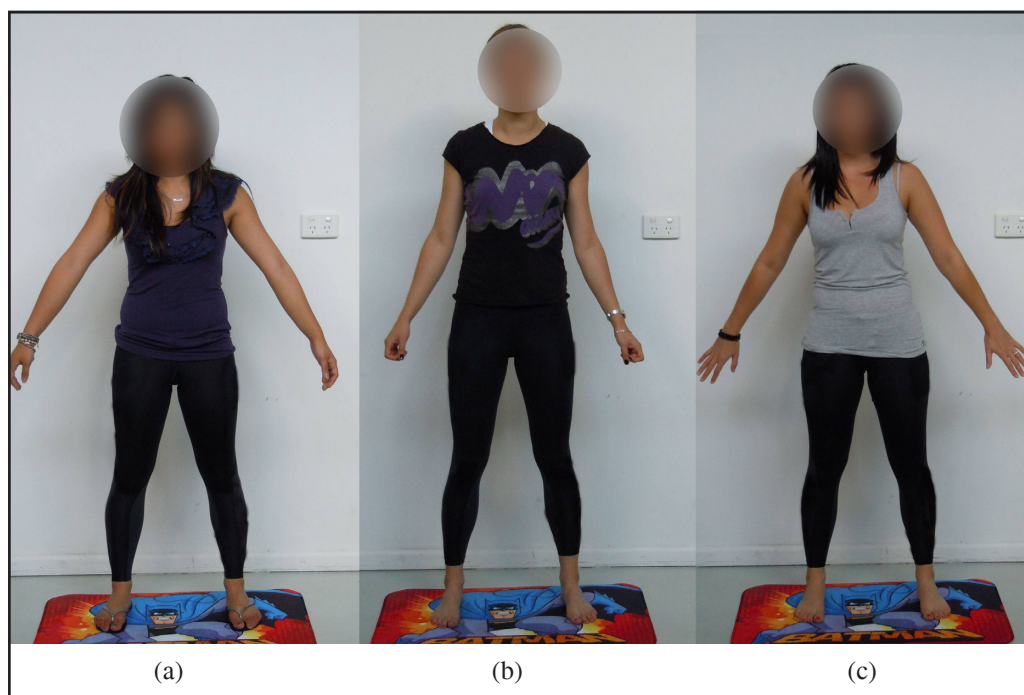


Figure 4. Posture photos of female models, W001, W002 and W003 – All Size S

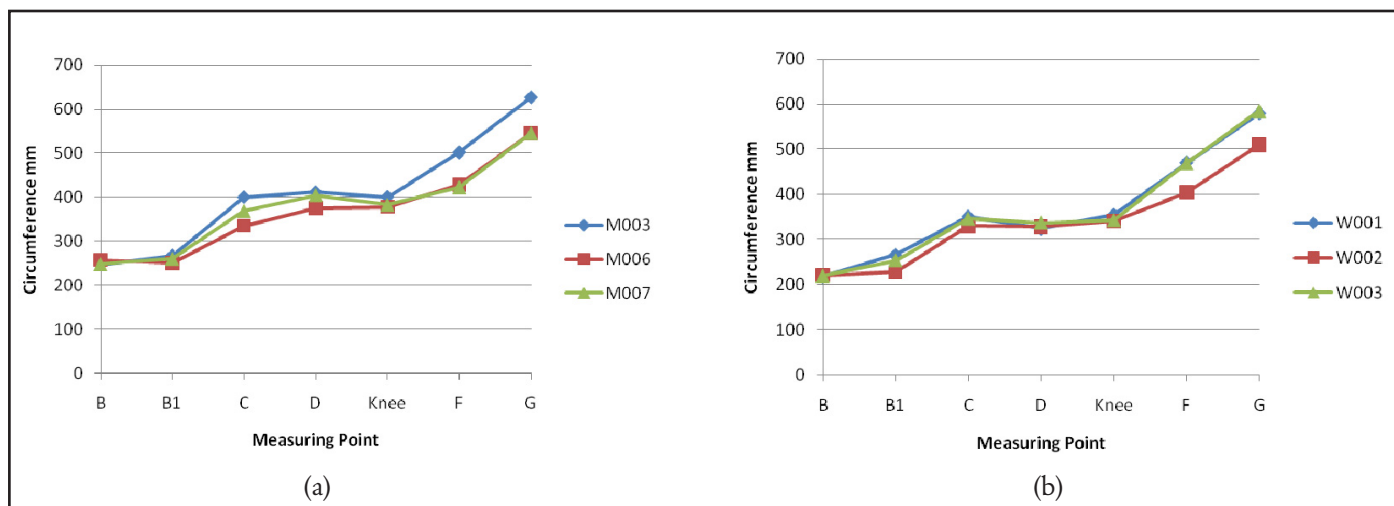


Figure 5. Circumference measurements at B-G on (a) male models in M and (b) female models in S

thus the males had longer thighs than the 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.

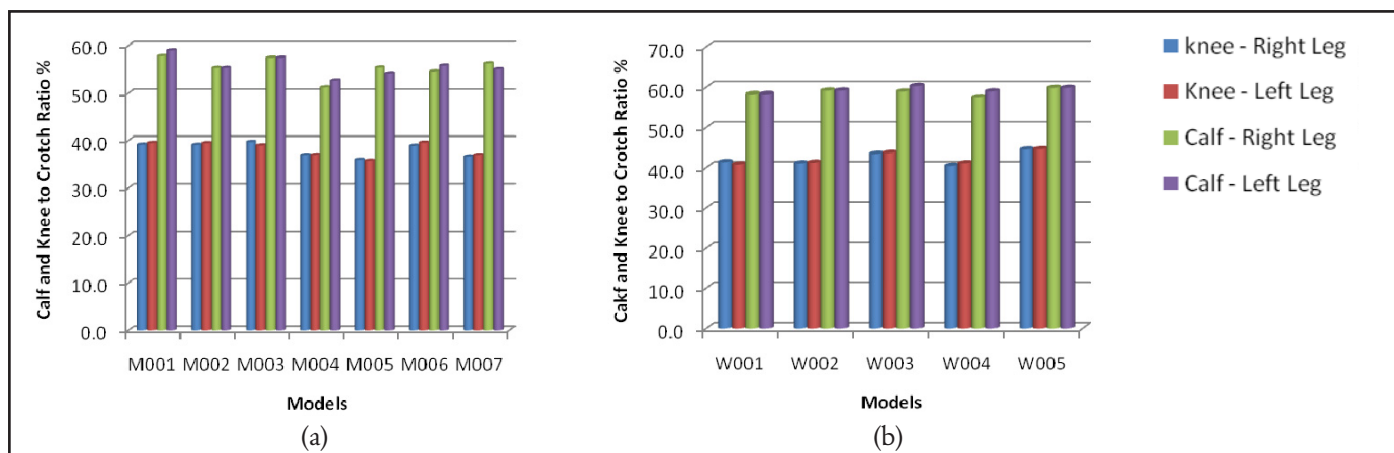


Figure 6. Calf and knee height to crotch height ratio (a) male models and (b) female models

Conclusion

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 3D Body Scanner, but can be used for other scanning software and generation of a 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 could then be extracted and used for the future evaluation of 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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