

# Changes in the Volume and Circumference of the Torso, Leg and Arm after Cycling in the Heat Determined Using 3D Whole Body Scanners

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## Abstract

Whole body volume changes due to sweat loss after exercise in the heat are well documented, but little is known about the relative contribution of the torso and extremities to these volume changes. It is the purpose of this study to quantify these effects. Therefore, seven healthy male subjects were scanned using a SizeStream and Vitronic whole body scanner prior to and shortly after they lost  $1.7 \pm 0.1\%$  of their body weight due to cycling at 2 W/kg in a 35°C, 20% relative humidity climatic chamber for 75 minutes. Whole body volume loss was  $1.0 \pm 0.7\%$  using the SizeStream scanner and  $1.3 \pm 0.6\%$  using the Vitronic scanner. Torso volume decreased most with  $2.1 \pm 1.5\%$  ( $p=0.009$ ) and  $5.6 \pm 3.1\%$  ( $p=0.002$ ) followed by the legs with  $1.1 \pm 2.7\%$  (N.S.) and  $2.9 \pm 1.0\%$  ( $p<0.0001$ ) for SizeStream and Vitronic respectively. Changes in arm volume were negligible. The circumference decreased significantly for the chest and upper legs but not for the waist and arms. We conclude that the major part of sweat loss originates from the torso and legs, but since both scanners did not produce similar results likely due to differences in accuracy, we recommend using high-resolution scanners to record volume changes in more detail.

**Keywords:** 3D scanning, body volume, fluid shift, sweat loss, heat strain, circumference, anthropometry

## 1. Introduction

Human cooling power during exercise in the heat mainly depends on the capacity to evaporate sweat from the skin. The inability to evaporate sufficient sweat leads to a strong increase in body temperature during exercise. For every 1°C increase in body core temperature, gross efficiency decreases by approximately 1% and this can seriously compromise performance [1]. A high body core temperature may eventually lead to premature cessation of exercise or the occurrence of heat related problems [2]. Therefore, knowledge on sweat evaporation is essential to increase performance in the heat and prevent undesired hyperthermia. After the initial work of Kuno ([3], research on sweat evaporation has gained more interest in the last three decades [4-7].

Two investigation methods are generally used to quantify wet heat loss from the skin. First, body weight is determined prior to and after exercise and the difference is equalled to the amount of evaporated sweat. When necessary, corrections are made to account for sweat that is accumulated in garments or that has dripped off from the skin. The second method is the measurement of local sweat evaporation. Some examples of this method are: measuring the moisture content in air led over the skin in small cups, counting stained sweat drops and weighing of absorption materials. The use of these various measurement tools and protocols makes it difficult to compare studies on sweat evaporation. Also, it cannot be excluded that the selected method had an impact on the results and thus confounding may have occurred [7]. However, it is worth to note that as more knowledge becomes available, fewer protocols will be interpreted incorrectly and the usage of measurement tools will improve. The sweat absorption method was recently used to generate sweat maps for the human body [8]. Despite considerable inter-individual variability, it was shown that the highest sweat rates were observed at the centre of the back and forehead [8].

What is essentially unknown is where the fluid that is excreted by the sweat glands is derived from. Is it derived from local fluid sources or is the fluid derived equally from all parts of the body? In order to investigate this question, we used 3D whole body scanning techniques to quantify volume and circumference changes in the torso, arms and legs. 3D whole body scanners can make accurate copies of the body [9]. Recently, the cost of 3D body scanners decreased drastically [10]. Therefore,

they can be added with low cost to the inventory of a thermal lab. However, a lower price may come with the expense of resolution and accuracy. Therefore, we investigated an inexpensive (SizeStream) and a state-of-the-art whole body scanner (Vitronic) and compared the results.

The human body can be compartmentalized in arms, legs and torso/head. The volume change of each compartment depends on the inflow (arterial flow), outflow (venous and lymphatic) and fluid loss through the skin or lungs. We hypothesized that the relative volume of the torso would decrease more than that of the arms and legs after exercise since the highest sweat rates are observed in the torso region [8]. Also, we hypothesized that the volume of the legs would decrease more than that of the arms since venous and lymphatic flow back to the body is enhanced by the muscle pump [11, 12]. Moreover, Ayling found no evidence of increased evaporation in the leg while cycling even though the skin temperature of the legs is higher and the airflow around the skin of the legs is increased due to the cycling movement [13]. Also, we hypothesized that the Vitronic 3D body scanner would provide a more accurate estimation of body volume loss than the SizeStream 3D body scanner.

## 2. Methods

### 2.1. Participants

Seven male volunteers who exercised regularly (3-5 times per week) and with no overweight (BMI 20-25) participated in this study, approved by the Ethics Committee of the Department of Human Movement Sciences (VU University Amsterdam). Their physical characteristics were: body weight  $78 \pm 7$  (standard deviation) (range 68 - 88) kg, stature  $188 \pm 6$  (range 181 - 200) cm, age  $23 \pm 4$  (range 20 - 29) years. After receiving detailed information about the study, a written informed consent form was obtained and the subjects were screened for known contraindications to exercise in the heat.

### 2.2. Protocol

The subjects were asked to take two large glasses (> 470 ml total) of water the night before the experiment and two large glasses (> 470 ml total) prior to the experiment in excess of their normal dietary fluid intake [14]. This was to make sure the subjects were euhydrated when they started the experiment. The subjects were not allowed to drink or to use the toilet from the moment the pre-test measurements started until the the end of the experiment.

Four subjects participated in the morning session and three in the afternoon session. First, their body weight, stature, circumferences of upper-arms left and right, chest, waist and mid-thighs left and right) were measured according to ISO8559 [15] at TNO premises. The subjects were then scanned in the Vitronic 3D body scanner at Dutch Defence premises. The time between the measurements at TNO and the Vitronic 3D scan was approximately fifteen minutes. During scanning the subjects were dressed in tight pants and they wore a cap to cover the hair. When the scan was made, the subjects were standing relaxed in mid-inspiration with feet slightly apart and arms slightly abducted. The protocol was repeated in the Sizestream scanner at TNO premises. The time elapsed between the scan in the Vitronic 3D body scanner and the scan in the Sizestream 3D body scanner was approximately 20 minutes. The SizeStream 3D scanner made three consecutive scans, and the calculated average values were further processed.

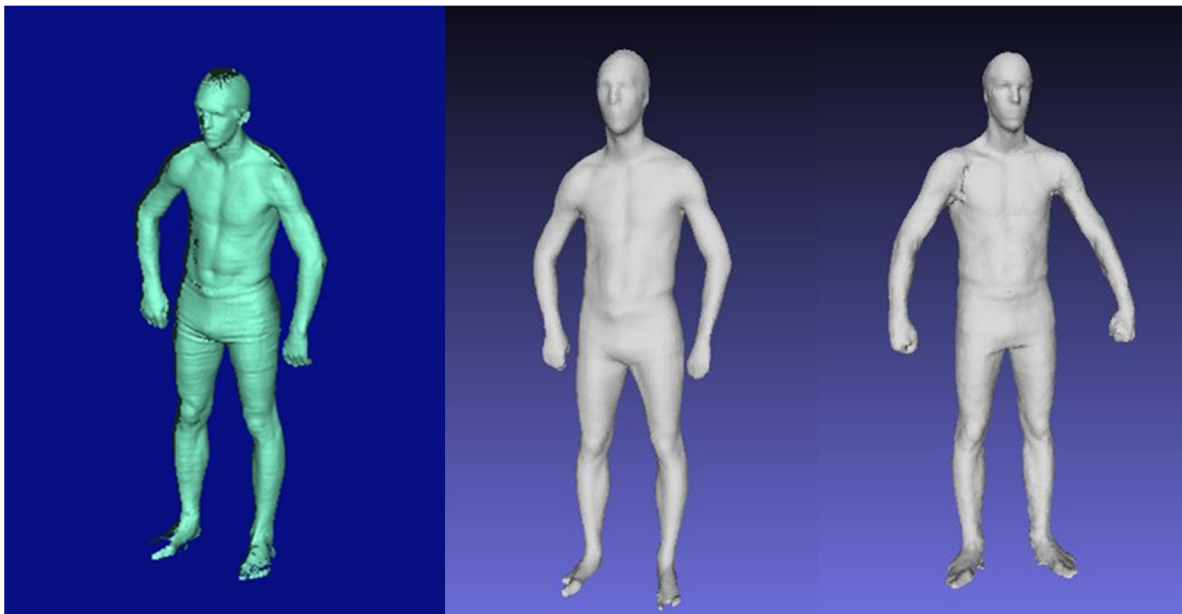
After scanning, the subjects entered the climatic chamber - set at 35°C and 20% relative humidity - where they had to cycle for 75 minutes at 2 W/kg dressed in shorts, shoes and socks. During the experiment their body weight, heart rate and skin temperature were measured every 15 minutes and they were asked for their Rating of Perceived Exertion (RPE) and thermal sensation (TS). After they left the climatic chamber, the pre-test measurements were repeated.

### 2.3. Materials

The subjects performed the cycle-ergometer test on one of the four available cycle-ergometers (2 Lode Excalibur, 1 Jaeger ER900, 1 Ergoline ergoselect 200P). Subjects were scanned in two different 3D body scanners (Sizestream 3D body scanner and Vitronic 3D scanner type Smart) before and after the climatic chamber sessions. One of the four measurement stands of the Vitronic scanner was dysfunctional and therefore the missing data was filled using local curvature ([16]. The body weight of the subjects was measured using a weight scale (Sartorius F300S, Göttingen, Germany) with an accuracy of 0.001 kg, the heart rate using a Polar heart rate monitor (Polar Electro, Finland) around the torso, skin temperature using 4 thermistors (Yellow Springs Type 400) which were attached with tape to the skin (neck, right scapula, right shin, left hand, according to ISO9886[17]). Rating of Perceived Exertion was assessed using the RPE scale [18], and thermal sensation using a 7-point scale from 'cold' to 'hot' [19]. Body circumferences were determined with a regular measuring tape.

## 2.4. Data processing and statistics

Volumes and circumferences of the left and right arm and left arm and leg were averaged for arm and leg. For the Vitronic scanner, circumferences of the upper leg, upper arm, waist and chest were calculated using Integrate [20]. A horizontal slice of 43, 25, 20 and 20 mm was taken for the analysis for the arm, leg, chest and waist respectively. The slices were selected at the belly of the biceps brachii and hamstrings, at the level of the chest nipples and belly button respectively. The volumes of the different body parts of all participants, scanned in the Vitronic 3D body scanner, were measured using Meshlab (<http://meshlab.sourceforge.net/>). For every body part the same cut-off points were used to make sure that the segments were identical for each scan. Fig. 1 shows example 3D scans.



*Fig. 1 Images from 3D scans of a selected subject. Left: unprocessed Vitronic scan; Mid: processed Vitronic scan; Right: SizeStream scan.*

The volumes and circumferences of participants' different body parts, scanned in the SizeStream 3D body scanner, were calculated by the standard processing software supplied with the SizeStream scanner.

Differences between the pre- and post-test circumferences and volumes of the different body parts were calculated by subtracting the pretest value from the posttest value and evaluated using Statistica 12. A Paired Samples T-Test was used to see if these differences were significantly different from zero. The relationship between changes in circumferences and volume between both 3D body scanners was established with linear regression analysis and the Pearson product-moment correlation coefficient. Results were considered significant at  $P < 0.05$ . Values are reported as mean  $\pm$  SD.

## 3. Results

### 3.1. Exercise in the heat

During exercise in the heat, mean skin temperature stabilized at about 33.7°C within 15 minutes. Mean heart rate stabilized at 160 bpm after 45 minutes of exercise. RPE and TS showed a continuous increase (Fig. 2). Weight loss was 0.26 kg for each 15 minute measurement interval in the first hour and slightly higher in the last period (Fig. 3). On average, the subjects lost  $1.35 \pm 0.16$  kg due to the cycling in the heat, similar to body weight loss of  $1.73 \pm 0.13$  %.

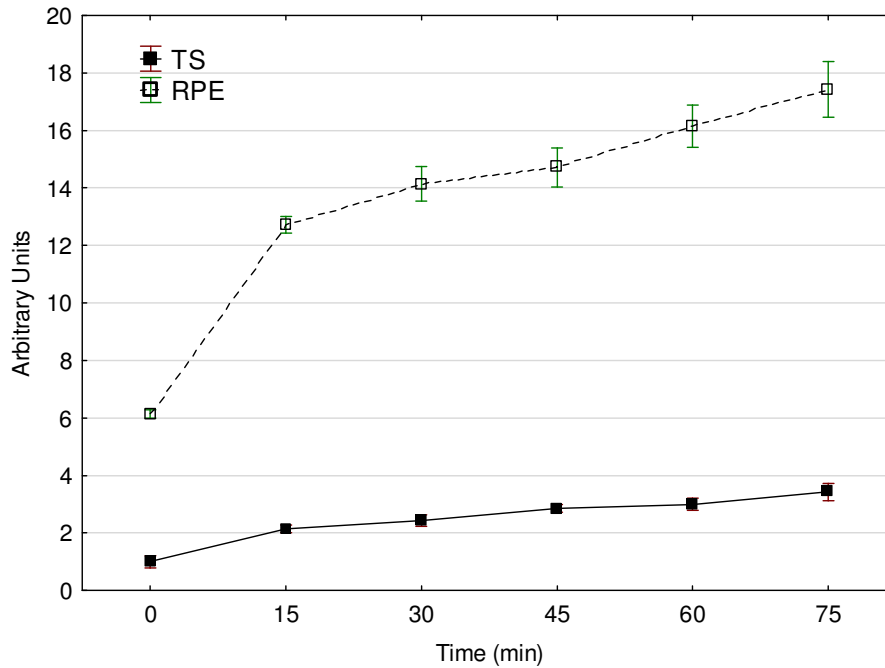


Fig 2. Thermal Sensation (TS) and Rating of perceived exertion (RPE) during the 75 minute exercise period averaged over 7 subjects with vertical bars indicating standard error.

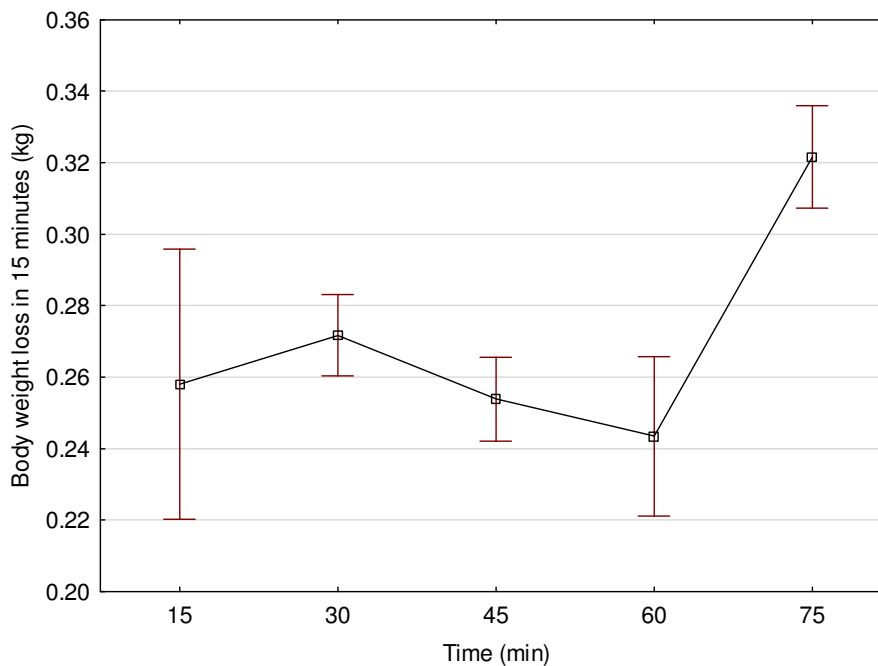


Fig 3. Body weight loss (kg) over the preceding 15 minutes during the 75 minute exercise period averaged over 7 subjects with vertical bars indicating standard error.

### 3.2 Volume changes

The volume changes of the whole body and arms, legs and torso are shown in Table 1. The whole body volume is generally overestimated in whole body scanning as compared to traditional methods like under water weighing [21] and this is also the case in this study. The SizeStream 3D body scanner estimated the body volume 2.8% higher than the Vitronic. The specific weight of the body (body mass divided by body volume) averaged 0.98 kg/L for the Vitronic and did not change due to cycling in the heat. For the SizeStream, the specific weight increased from 0.952 to 0.962 kg/L ( $t=3.6$ ,  $P=0.01$ ).

Table 1. Volume changes (dm<sup>3</sup>) of the whole body, body without head, feet and hands, torso, arms and legs measured by the Vitronic and SizeStream scanner averaged over 7 subjects with standard deviation. The difference is the percent change from the pretest to the posttest.

	Vitronic Pre	Vitronic Post	Vitronic difference (%)	SizeStream Pre	SizeStream Post	SizeStream difference (%)
Whole body	79.6 ± 7.3	78.6 ± 7.5	1.3 ± 0.6*	81.8 ± 7.0	81.0 ± 6.9	1.0 ± 0.7*
Body without legs, arms and head	71.7 ± 7.1	70.5 ± 7.0	1.8 ± 0.4*	72.6 ± 6.7	71.7 ± 6.8	1.2 ± 0.7*
Torso	10.0 ± 0.7	9.5 ± 0.8	5.6 ± 3.1*	50.1 ± 3.5	49.1 ± 3.8	2.1 ± 1.5*
Arms	-	-	-	5.0 ± 0.8	5.0 ± 0.8	0.4 ± 4.3
Legs	5.0 ± 0.7	4.8 ± 0.7	2.9 ± 1.0*	10.9 ± 1.0	10.8 ± 1.1	1.1 ± 2.7

\*significantly different (P<0.01).

The torso ‘slice’ of the Vitronic 3D body scanner shrunk by more than 5% due to sweat loss; the entire torso volume assessed by the SizeStream 3D body scanner also dropped significantly (Table 1). Arm volume assessed by the SizeStream 3D body scanner did not change. Upper leg volume dropped significantly for the Vitronic scanner; leg volume assessed by the SizeStream did not change. The volume of the arms in Vitronic could not be determined due to occlusion effects (some skin segments were not reachable by the laser or invisible for the cameras), but circumference could be determined and is shown in the next section. For the Vitronic only the upper leg was measured, the SizeStream returned volume of the entire leg.

### 3.3. Circumference changes

The circumferences of the body parts are shown in Fig. 4 for manual measurements and prior to and after the cycling experiment for the Vitronic and SizeStream 3D body scanner.

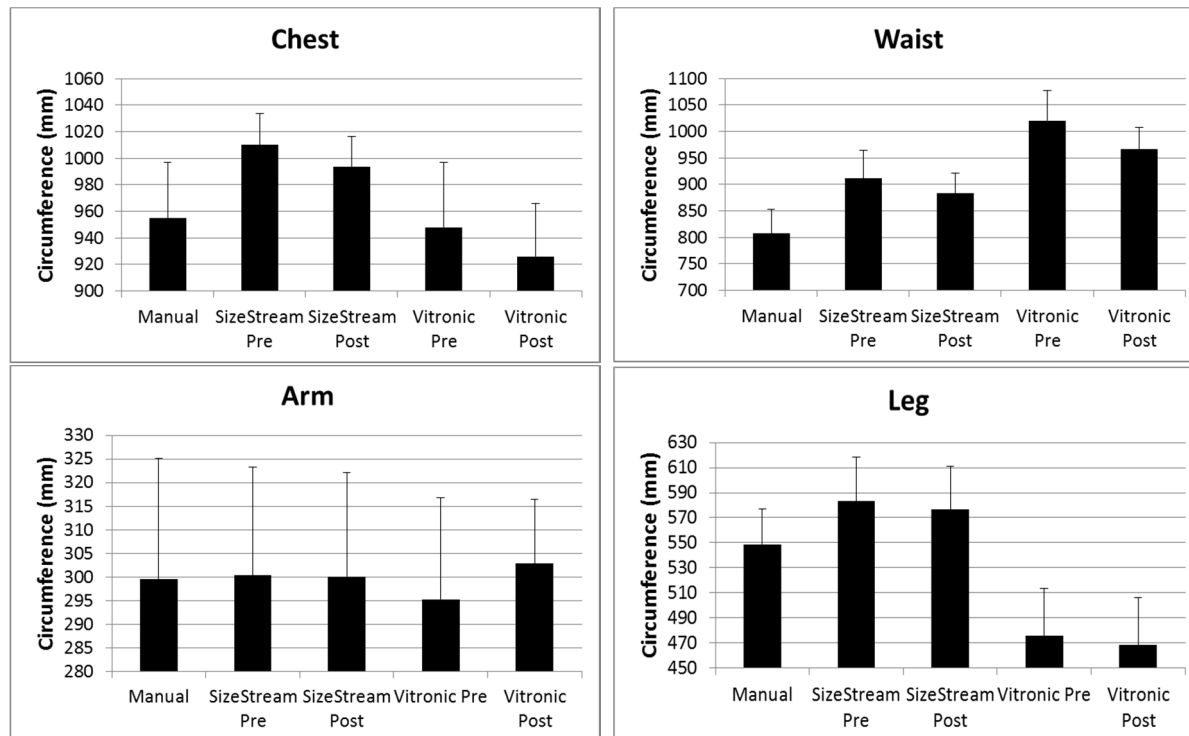


Fig. 4 Circumferences of the chest, waist, upper arm and upper leg measured manually and derived from the SizeStream scan and Vitronic scan prior to and after cycling in the heat. \* = significantly different.

The cycling in the heat did not influence the circumference of the arms. The average drop in circumference of the waist was 3% for the SizeStream and 5% for the Vitronic, but this was not significant likely due to the large interindividual variation. The circumference of the chest dropped significantly by about 2% for the Vitronic ( $t=3.99$ ,  $P=0.007$ ) and SizeStream ( $t=3.34$ ,  $P=0.016$ ) (Fig. 4). Circumference of the legs dropped significantly by about 1.3% for the Vitronic ( $t=3.67$ ,  $P=0.010$ ) and SizeStream ( $t=3.07$ ,  $P=0.022$ ).

### 3.4. 3D body scanner comparison

The volume change of the whole body determined by the Vitronic and the SizeStream 3D body scanner is shown in Fig. 5. No significant correlation was found between the two measurements. ( $r=-0.1$ , N.S.). Similarly, no significant relationship existed between the circumference differences and other volume differences between the Vitronic and SizeStream on an individual level.

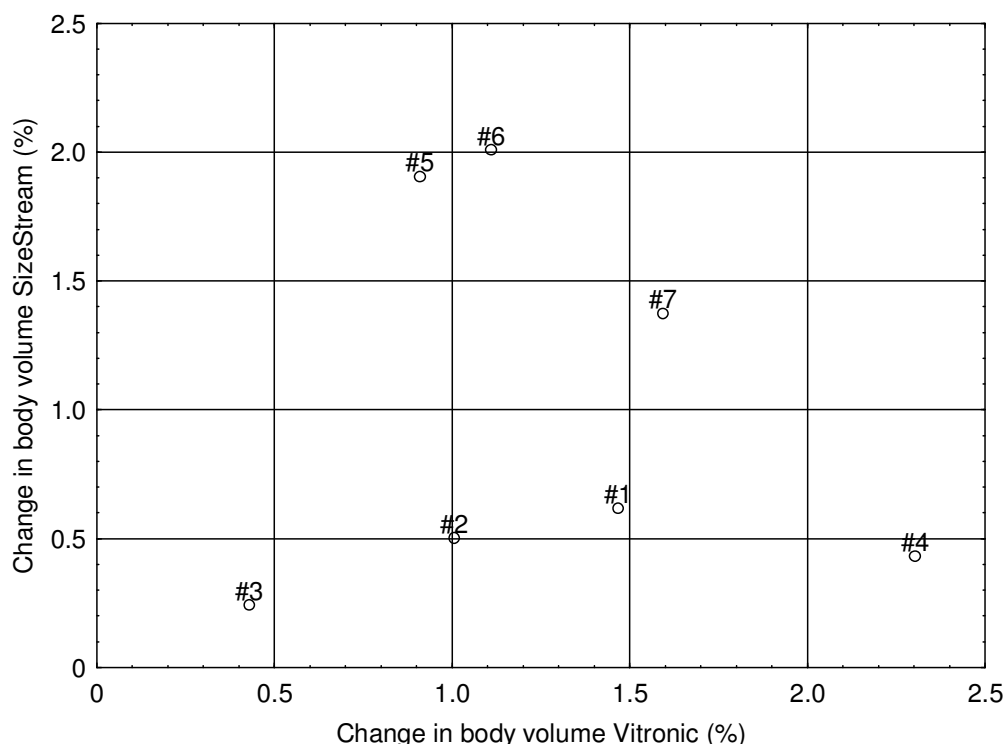


Fig. 5 Relationship between whole body volume change determined by the Vitronic scanner (horizontal axis) and SizeStream scanner (vertical axis).

### 3. Discussion

This study aimed to provide insight into the anatomic origin of fluid lost through evaporation of sweat. The volume of the torso decreased considerably more (5.6 and 2.1% for the Vitronic 3D body scanner and the SizeStream 3D body scanner, respectively) than that of the whole body (1.3 and 1.0% respectively). Therefore, a larger than average amount of fluid loss comes from the torso. This is even more so since the torso has a relatively low surface to volume ratio compared to other body parts. The investigated part of the torso was smaller for the Vitronic 3D body scanner (a slice around the nipples) than for the SizeStream 3D body scanner, of which the standard software produced entire torso volume only. The relatively high fluid loss from the torso is in line with the observations from Smith [8]. This implies that the fluid lost by sweating is coming from local sources. For instance, no changes were observed in the volume of the arms or the circumference of the upper arms. These locations are known to produce less sweat (Smith and Havenith 2011), in particular when the relatively large surface area is taken into account. The legs did decrease in circumference and volume (Vitronic 3D body scanner only). The legs produced the power for the cycling exercise and it is not unlikely that the volume of the muscle tissue was affected by the cycling exercise due to increased blood supply to the exercising muscles. However, no evidence for this phenomenon could be found in the literature.

The observed rate of fluid loss in our experiment of about 1.7% of body mass in 75 minutes is in line with earlier studies [22]. It is claimed that after heat acclimation, the sweat rate in both arms and legs increases more than in other parts of the body [23-25]. As our experiment took place in early spring, it is unlikely that the subjects were heat acclimated.

Ayling [13] concluded that the legs produce considerable amounts of metabolic heat during cycling. Therefore, according to Ayling, the skin temperature of the upper leg will increase during cycling enabling easier evaporation of sweat from the skin. In our study, upper leg temperature was not measured, but the temperature of the shin did not increase after 15 minutes of exercise and mean skin temperature was stable as well. We do agree with Ayling that the increased air flow along the legs during exercise can possibly stimulate the evaporation of sweat in the legs. In comparison to the active legs, the arms were not active during the cycle ergometer test, thus the relatively passive arms were not stimulated to enhance the evaporation of sweat. Also, the venous return is stimulated by the muscle pump, and is therefore lower in the arm during cycling. This may explain why a decrease in volume and circumference in the legs was observed and not in the arms.

The results of Smith & Havenith [8] and their sweating maps show a lot of similarities with our results and our own body maps. Our hypothesis was also partly based on their sweating maps. When comparing the sweating maps of Smith and Havenith [8] with our data, it appears that the largest volume changes occur at the body parts where the most evaporation of sweat takes place. A clear example of this conclusion is the torso.

The use of 3D scanning systems for body volume determination is not new. Wells et al. [21] concluded that three-dimensional scanning for measuring body volume may be a potential and reliable technique based on comparison with under water weighing, bodpod and dexta scan. Increasingly, 3D scans are used to quantify the volume of the air gap in between the human body and garments, since there is a link with garment fit and heat strain [26]. One would expect that the observed changes in volume and circumference for each subject would be similar for both scanner types in the current experiment. However, Fig. 5 shows that the differences can be considerable. The Vitronic scanner has the highest resolution (about 32000 vertices for a subject versus 15000 for the SizeStream scanner). Therefore, the results from the Vitronic system can be considered to be more reliable, even though one camera was out of order. Very high resolution scanners that are extremely fast (acquisition time of a few milliseconds) are now available [10] and it is recommended to use these scanners to refine the observations from this study so that for instance the fluid shifts in the feet and hands can be monitored. In our study, the feet and hands could not be scanned reliably (see Fig. 1).

In conclusion, we showed that in subjects losing about 1.7% of their body weight, the decrease in volume and circumferences of the torso and legs was disproportionately larger than the whole body volume loss. This supports the notion that local fluid loss is not compensated by fluid from other body parts. The use of ultra-high resolution 3D whole body scanners may further enhance the insight in compartmental fluid shifts after exercise in the heat.

#### 4. Acknowledgments

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