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Reproducibility of kinematic measures of the thoracic spine, lumbar spine and pelvis during fast running

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1 Introduction

Developing a reproducible kinematic protocol for quantifying spinal kinematics during running is difficult for a number of reasons. Firstly, the spine is a multi-articulate structure and, in order to describe its motion using a skin-based marker system, it is necessary to develop a simplified rigid body model in which all motion is assumed to occur at a small number of joints. Secondly, with increased movement speed, there is an increase in soft tissue movement and the potential for increased shock loads to cause unwanted vibration in skin mounted marker sets [1]. Finally, with any human movement, there is an associated degree of between-trial variability [2]. These different sources of variability will combine with the instrumental errors of a motion capture system (typically 1°) and any between-day variability in marker placement to give a fundamental limit to the accuracy of kinematic measurement.

There have been a number of studies investigating the kinematic reliability of spinal and pelvic motion during walking [3, 4]. However, although a few authors have attempted to describe pelvic/spinal motion during running [5-7], there has only been one study investigating kinematic reliability [8]. This study investigated the reproducibility of pelvic motion, using markers attached to the anterior superior iliac spines (ASIS) and sacrum, and lumbar spine motion using a wand mounted over the 12th thoracic spinous process. Although Schache et al. [8] were able to demonstrate good reproducibility in most body planes, there were a number of limitations to the study. Firstly, data was collected during treadmill rather than over ground running and participants ran at a relatively slow speed of 3.9ms^{-1}. It is therefore not clear whether good reproducibility would be obtained at higher running speeds, typical of elite distance runners. Secondly, although the marker wand gave repeatable results at this slow speed, it is possible that, at higher running speeds, there could be increased inertial motion leading to greater measurement variability. Finally, Schache et al. did not include a thoracic segment in their kinematic protocol.

In order to minimise the effect of soft tissue artefact on derived segmental kinematics, Lu and O'Connor [9] have proposed the use of a global optimisation (GO) technique which imposes specific joint constraints. Using modelling approaches, this approach has been shown to produce kinematic trajectories which are closer to true bone motion than trajectories obtained using a 6DOF (degrees of freedom) approach [9, 10]. It is claimed that GO reduces the effect of soft tissue artefact. However, no experimental studies have investigated whether it could reduce kinematic variability during running.

We undertook the current study to assess the reproducibility of a new protocol for quantifying pelvic and lumbar/thoracic spine motion during over ground running at a fast speed. In addition, we sought to compare measures of reproducibility derived using GO with a 6DOF approach. In order to compare with previous running studies, we also quantified the kinematic reproducibility of lower limb kinematics.

2 Methods

2.1 Subjects, procedures and instrumentation

A cohort of 12 subjects (11 male), who all ran regularly at a competitive level, were recruited for this study. The mean (SD) age of the subjects was 23.25(4.3) years, mean height 1.64 (0.063)m and mean weight 60.45(8.13) Kg. Ethical approval was obtained from the Local Ethics Committee prior to the commencement of data collection.

Kinematic data were collected from each subject from the thoracic spine, lumbar spine, pelvis, thigh, shank and foot using 15mm markers. To track the motion of the thoracic spine, a rigid plate with three attached markers, was attached to the sternum [11] (Figure 1a) . In order to define an anatomical reference frame for this segment, markers were attached to C7, the spinous process of the sixth thoracic vertebra (T6), the suprasternal notch (IJ) and the xiphoid process (XP) [12]. Pilot work was performed in which the movement of a marker wand, similar to that used by Schache et al. [8], was recorded using a high-speed video camera. These images demonstrated considerable oscillation of the wand at higher running speeds (>4ms^{-1}). Therefore, in order to track the motion of the lumbar segment, a protocol proposed by Seay et al. [7] was used. With this approach an elasticon bandage is wrapped around the lumbar region from the level of the posterior superior iliac spine to the rib cage at the level of the T12-L1 joint space. Three markers were then placed over the lumbar spine at the T12–L1 joint space, L5-S1 joint space and midway between these two markers. Four more markers were then placed on the bandage either side of the midline markers (Figure 1b).

A pelvic segment was defined and tracked using markers placed over both ASISs and both posterior superior iliac spines (PSIS). Rigid plates, attached laterally at the distal end, were used to track motions of the thigh and shank segments and calibration markers were attached to the femoral epicondyles and ankle malleoli. The foot segment was defined using the malleoli markers and markers attached to the shoe over the first and fifth metatarsal heads. This segment was tracked using the metatarsal markers and a marker placed at the back of the shoe.

Kinematic data was collected using a 12-camera Qualisys Pro-reflex system, sampling at 240Hz, and kinetic data collected from 2 AMTI force plates embedded in the running track, sampling at 1200Hz. Static markers were removed after the calibration trial and subjects given time to warm up. Running data were then captured on a 32m indoor running track giving subjects sufficient distance to accelerate to the correct speed of 5.6m/s (30:00 10k pace). Running speed was measured using optical timing gates and 7-10 trials within ±2.5% of the target speed collected for each subject. The same investigator, an experienced physiotherapist, performed all static marker placements and subjects returned for a repeat test between 5 and 10 days following their initial visit. Both tests were conducted at the same time of day and subjects performed a similar level of exercise history in the 24 hours prior to testing.

2.2 Derivation of kinematic data and statistical analysis

In order to implement a GO model, it is necessary to impose constraints which limit rotation and/or translation between adjacent segments. This is achieved by defining a constraint point between each segment, which corresponds to the joint centre. With the GO model used for this investigation, constraint points were positioned at the origins of all segment coordinate frames distal from the pelvis and expressed in the pelvic coordinate frame. The precise location of this coordinate frame did therefore not influence the GO calculations. The origin the of pelvic frame was positioned at the midpoint between the ASISs with the X axis pointing towards the RHS ASIS. The Y axis for this frame

pointed from the origin away from the midpoint of the PSIS markers and the Z axis was the common perpendicular and pointed upwards.

An anatomical coordinate frame for the thorax was constructed similar to ISB recommendations [12]. Firstly, a Z axis was defined as the line connecting the midpoint between PX and T6 and the midpoint between IJ and C7 and pointing upwards. The X axis was then defined as the line perpendicular to the plane formed by IJ, C7 and the midpoint between PX and T6 pointing right and the Y axis defined as the common perpendicular to the Z and X axes, pointing forward. In order to define an appropriate constraint point, the origin of the thorax coordinate frame was then shifted to a position 5% along the line from T12 to PX.

It is difficult to define an anatomical coordinate system for the lumbar spine and therefore the lumbar frame was aligned with the pelvic frame. However, the origin was positioned at a point 5% from the L5S1 marker to the pelvic origin (mid point between the ASISs) [7], again to ensure an appropriate constraint point for the global optimisation calculations. For each thigh, the Z axis pointed upwards and was aligned with the long axis of the bone, defined from the hip joint centre (predicted from the ASIS and PSIS locations [13, 14]) and the midpoint of the knee epicondyles. The X axis pointed right and was perpendicular to the Z axis and in the plane containing the knee epicondyles and hip joint centre and the Y axis was defined as the common perpendicular. The shank coordinate frame was defined in a similar way using the knee epicondyles and ankle malleoli and the foot segment was defined from the ankle malleoli and the markers on the first and fifth metatarsal heads. For the final angular kinematic data, X axis rotation corresponded to sagittal plane motion, Y axis rotation to frontal plane motion and Z axis rotation to transverse plane motion.

Two methods were used to derive segmental kinematics: a six degrees of freedom model (6DOF) and a global optimisation (GO) model. For both approaches motion data was filtered with a 10 Hz Butterworth filter. With the 6DOF model, no joint constraints were imposed, each segment was treated independently and Cardan angles were calculated in XYZ sequence. With the GO approach, a set of joint constraints were imposed in which segments could rotate with 3DOF but not translate relative to adjacent segments. Segmental kinematics were obtained at each time frame by using the optimisation approach proposed by Lu and O'Connor [9] to solve for the orientations of the constrained multi-link model. Right initial contact was identified from the force platform data and, in order to define a complete gait cycle, a second right initial contact was identified as the time when the ankle, knee and hip angles were the same as for the first initial contact. All kinematic calculations were implemented in Visual 3D (C-Motion) and then outputted to Matlab for statistical analysis.

Two metrics were used to quantify within and between-day reproducibility of the derived kinematics. The first , the coefficient of multiple correlation (CMC), gives a measure of waveform similarity which tends to one for identical waveforms and zero for dissimilar waveforms [4, 15]. For this study CMC values of approximately 0.8 or greater were considered indicative of good reproducibility. Secondly, in order to quantify the absolute angular differences between trials, the standard error of measurement (SEM) averaged over a complete gait cycle, was used. Following the suggestions of McGinley et al. [16], angular differences of 2° of less were considered to be good reproducibility and angular differences between 2°-5° considered reasonable.

3 Results

Between-day reproducibility of the thorax and of the lumbar spine with respect to the pelvis was good in the frontal and transverse planes (Tables 1 and 2). Relatively low SEMs values were also obtained for the thorax with respect to the lumbar spine in these two body planes. However, for some subjects, it was not possible to calculate the bCMC because of insufficient similarity between the day 1 and day 2 data. This indeterminacy occurred more often with the 6 DOF compared to the GO approach (Table 1). In general relative sagittal plane motion of the spinal/pelvic segments demonstrated slightly lower reliability than the other two body planes and there were a number of instances in which the bCMC was indeterminate with both the 6 DOF and GO approach. Inspection of the data revealed that for these subjects, although waveforms were very similar, there were between-day shifts in curve offset which outweighed the overall variability in the curve.

TABLE 1 ABOUT HERE

Motion of the thorax with respect to the laboratory coordinate frame generally gave good reproducibility in all body planes (Tables 1 and 2). Good reproducibility was also found for the pelvis and lumbar segments in the frontal and transverse planes (Tables 1 and 2). However, the reproducibility was slightly lower in the sagittal plane, and again the bCMC was indeterminate for a few subjects. Inspection of the data again confirmed the similarity of waveform shape but showed that there were shifts in curve offset. In general, when both relative spinal/pelvic motion and motion of the segments in the lab were considered the reproducibility was similar between the 6DOF and the GO approaches. However, there were slightly more instances in which the bCMC were indeterminate with the 6DOF approach.

TABLE 2 ABOUT HERE

High bCMC values were obtained for the sagittal plane motion of the hip, knee and ankle (Table 1). Interestingly, in this body plane, bSEM values were found to be only slightly higher than the wSEM values. Poor reproducibility was observed for transverse plane motion of the lower limb with bSEM values of up to 6.3° (Table 2). *In the sagittal plane, the GO approach gave slightly lower bSEM values for the knee and ankle than the 6 DOF approach, whereas for the hip, the 6 DOF data appeared slightly more reliable.*

4 Discussion

The results of this study demonstrate that, in most body planes, the movements of the spine and pelvis can be measured reproducibly between different days. Interestingly, between-day SEM values were only slightly higher than within-day values for several of the derived kinematic trajectories (Table 2). This illustrates that a large proportion of the observed variability was due to either soft tissue artefact or genuine differences in movement coordination between trials and not due to variability in marker positioning. As data was collected from lean subjects who were elite athletes, and therefore likely to have very consistent movement patterns, it will give an indication of a minimal level of within-day movement variability at higher running speeds.

Lower levels of between-day reproducibility were observed in sagittal plane motion, especially for the motion of the lumbar spine/pelvis with respect to the lab and for the motion of the thorax with respect to the lumbar spine. Inspection of these data showed that, that in all cases the kinematic

waveform was very similar between days but that there were shifts in curve offset which produced an indeterminate bCMC. This effect has been observed in previous repeatability studies [8]. It is possible that these shifts may have arisen from genuine differences in day-to-day coordination, possibly due to subtle differences in postural alignment between testing sessions. Alternatively, the shifts may have resulted from errors in repositioning either the ASIS or the PSIS markers (used to define both the pelvic and lumbar frames). It has been argued that errors in PSIS marker repositioning of ±8.4mm can lead to an offset in pelvic motion of ±3.7°, similar to the values observed in our data. It may therefore be advisable in future studies to use a number of additional bony landmarks to define the pelvic segment or to use a device for more accurate marker repositioning [17].

The results of this study demonstrated that, on average, similar levels of reproducibility are obtained using either the 6DOF or the GO approach. A poor match between the day 1 and day 2 waveforms was highlighted by an indeterminate bCMC. Although this occurred most readily in the sagittal plane, due to curve offsets, it also occurred occasionally in the other two body planes and was more readily observed with the 6 DOF approach, suggesting marginally better performance of the GO algorithm. However, overall there was no clear data to indicate improved reliability with the GO approach. It has been suggested by previous modelling studies that GO is able to reduce the effects of soft tissue artefact [9, 10]. Therefore these results may suggest that the main source of the observed variability may not be soft tissue movement, but may be the inherent variation in day-to-day movement patterns.

Only one previous study has investigated the kinematic reproducibility of the hip, pelvis and lumbar spine during running [8]. However, these investigators looked at treadmill running at a precise speed which may result in less trial-to-trial movement variability. Interestingly, their reported bCMC values (0.876-997) are similar to those found in the current study for lumbar-pelvic-hip motion. Similar to our findings, they were sometimes unable to calculate sagittal plane bCMCs for the pelvis and lumbar spine with respect to the lab. However, unlike the present study, they also observed this problem for lumbar spine with respect to the pelvis in the sagittal plane. In addition to CMCs, Schache et al. [8] also reported maximum root mean square differences between days for each kinematic curve. These values were typically twice the bSEM values obtained in our study (Table 2), suggesting comparable reproducibility.

Most previous studies investigating the reproducibility of running kinematics of the lower extremities have looked at specific gait parameters instead of quantifying the average deviation across the gait cycle [18, 19]. For example Noehren et al. [17] reported SEM values for sagittal motion of the hip (5.1°), knee (1.9°) and ankle (1.4°) for peak excursion, suggesting slightly better reproducibility than the current study. This difference may be attributed to the higher speeds used in this study which may have resulted in relatively high levels of within-day variability.

There a number of limitations to this study. Firstly, the lumbar and thoracic spine were both assumed to be single rigid segments. Although this is a highly simplified model of spinal motion, it is an appropriate first step for developing an understanding of spinal motion during running and has been used previously to understand walking [20]. This approach would not capture subtle differences in intervertebral motion. However, it can easily be replicated in other laboratories and could therefore be used in future studies investigating running kinematics. *Another potential limitation is the use of lean, well trained athletes which may have resulted in levels of repeatability*

lower than those typical of recreational runners with more adipose tissue. However, this study was designed to understand repeatability during fast running and therefore it was appropriate to use a subject group well practiced at running at higher speeds. It is possible that variability would be reduced at lower running speeds, however, further investigation would be needed to investigate this.

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Tables:

Table 1: Coefficient of multiple correlation, calculated within-day (wCMC) and between-day (bCMC) for both the 6 degrees of freedom model (6DOF) and the global optimisation approach (GO). The CMC was calculated separately for each subject and then, in most cases, averaged across the 12 subjects. However, for some subjects, lower levels of reproducibility produced an indeterminate CMC and therefore. In these cases the CMC had to be calculated for [a]n=8, [b]n=9, [c]n=10 or [d]n=11 subjects. (The abbreviation Wrt standard for with respect to).

6 DOF	wCMC (x)	wCMC (y)	wCMC (z)	bCMC (x)	bCMC (y)	bCMC (z)
Thorax Wrt Pelvis	0.923	0.964	0.979	0.845[d]	0.92	0.968
Thorax Wrt Lumbar	0.823	0.893	0.942	0.679[a]	0.89[c]	0.917[d]
Lumbar Wrt Pelvis	0.945	0.984	0.991	0.743	0.911	0.942
Thorax Wrt Lab	0.901	0.893	0.98	0.868	0.947[d]	0.982
Lumbar Wrt Lab	0.896	0.942	0.978	0.794[c]	0.79	0.952
Pelvis Wrt Lab	0.858	0.96	0.971	0.774[b]	0.887	0.971
Right Hip	0.997	0.975	0.924	0.995	0.942	0.662[b]
Right Knee	0.996	0.949	0.974	0.997	0.698[b]	0.876
Right Ankle	0.988	0.951	0.949	0.963	0.902	0.784
Global Optimisation	wCMC (x)	wCMC (y)	wCMC (z)	bCMC (x)	bCMC (y)	bCMC (z)
Thorax Wrt Pelvis	0.954	0.97	0.973	0.836[d]	0.955	0.943
Thorax Wrt Lumbar	0.838	0.897	0.946	0.667[b]	0.806	0.856[d]
Lumbar Wrt Pelvis	0.951	0.985	0.905	0.803	0.964	0.753[d]
Thorax Wrt Lab	0.923	0.914	0.983	0.855	0.886	0.987
Lumbar Wrt Lab	0.87	0.943	0.971	0.738[d]	0.821	0.944
Pelvis Wrt Lab	0.845	0.97	0.971	0.731[b]	0.947	0.97
Right Hip	0.996	0.966	0.922	0.991	0.951	0.755[b]
Right Knee	0.996	0.969	0.977	0.998	0.714[d]	0.759
Right Ankle	0.988	0.96	0.951	0.981	0.824	0.775[d]

Table 2: SEM values, calculated within-day (wSEM) and between-day (bSEM) for both the 6 degrees of freedom model (6DOF) and the global optimisation approach (GO). The SEM was calculated using the data from all 12 subjects at each point in the gait cycle. The tabulated values represent the mean across the gait cycle in degrees. (Note the abbreviation Wrt standard for with respect to).

6 DOF	wSEM (x)	wSEM (y)	wSEM (z)	bSEM (x)	bSEM (y)	bSEM (z)
Thorax Wrt Pelvis	2	1.5	2.2	3.1	2.2	2.6
Thorax Wrt Lumbar	1.7	1.3	2.1	3.5	1.8	3
Lumbar Wrt Pelvis	1	0.8	0.6	2.2	1.6	2.4
Thorax Wrt Lab	2	1.3	2.4	2.2	1.4	2.1
Lumbar Wrt Lab	1.5	1	1.7	3	1.9	2.7
Pelvis Wrt Lab	1.2	1	1.7	1.9	1.7	1.6
Right Hip	2.3	1.5	1.7	2.8	2.3	5.7
Right Knee	3.5	1.1	2	3.4	3.4	4.4
Right Ankle	2.6	2.2	1.6	4.2	3.1	3.6
Global Optimisation	wSEM (x)	wSEM (y)	wSEM (z)	bSEM (x)	bSEM (y)	bSEM (z)
Thorax Wrt Pelvis	1.5	1.9	1.7	3.6	2.4	2.2
Thorax Wrt Lumbar	1.6	1.3	1.5	3.9	1.8	3.2
Lumbar Wrt Pelvis	1.4	1.4	1.2	2.7	2	1.8
Thorax Wrt Lab	1.6	1.4	2.1	2.3	1.4	1.7
Lumbar Wrt Lab	1.9	1.2	1.9	3.1	2.2	2.6
Pelvis Wrt Lab	1.4	1.4	1.8	2.8	2	1.8
Right Hip	2.7	1.9	2.1	3.9	2.4	6.1
Right Knee	3.7	1.3	2	2.9	3.9	6.2
Right Ankle	2.6	2.3	1.9	3.1	4.4	4.5

Conflict of interest statement

There have been no financial incentives or personal relationships involved with other people or organisations in the preparation of this work that could result in inappropriate influence or bias.

There are no potential conflicts of interest including employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

Research was conducted on site at Salford University following ethical approval from University ethical committee. Supplementary processing was conducted also on site including the collection, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication. No sponsors were involved in this process.

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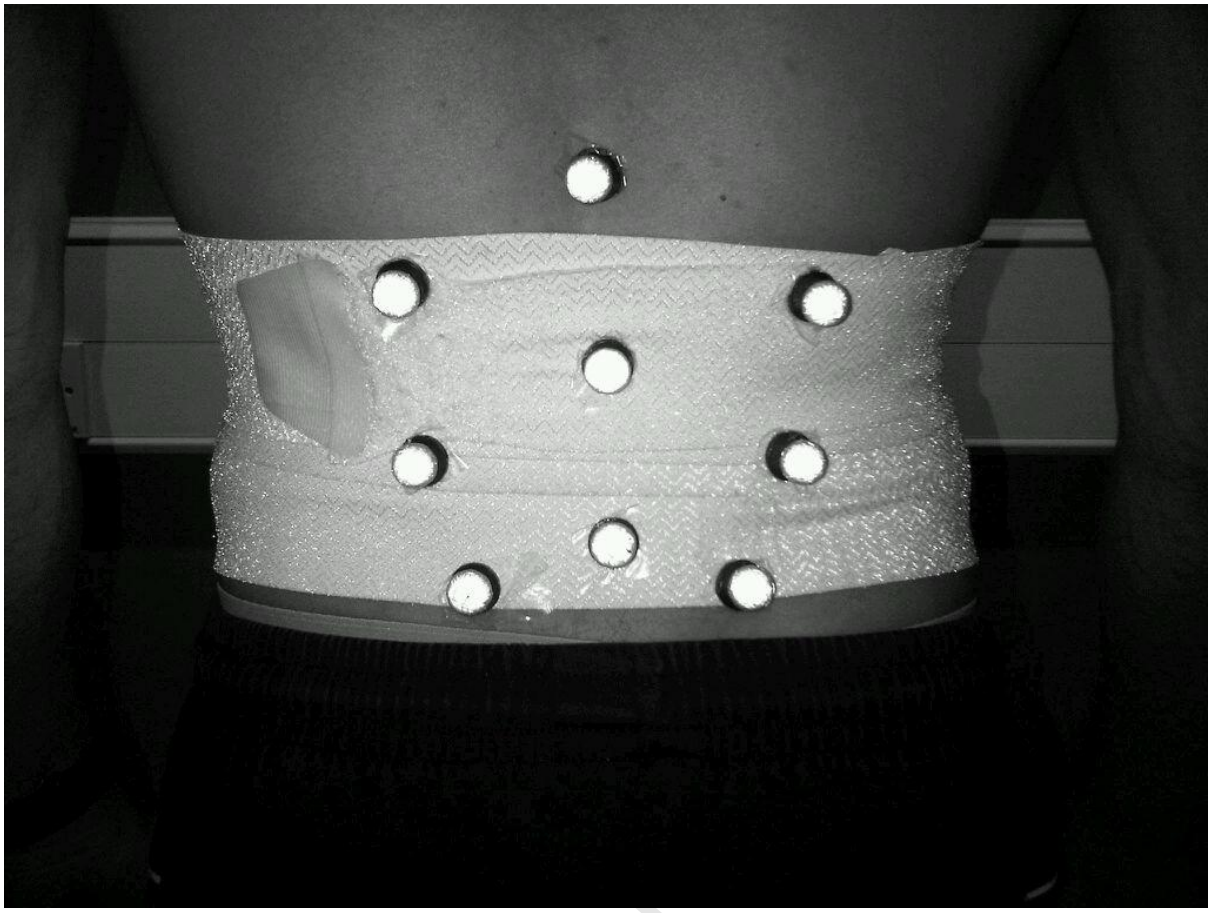

Figure 1a: Image of the marker set used to track the lumbar spine during running

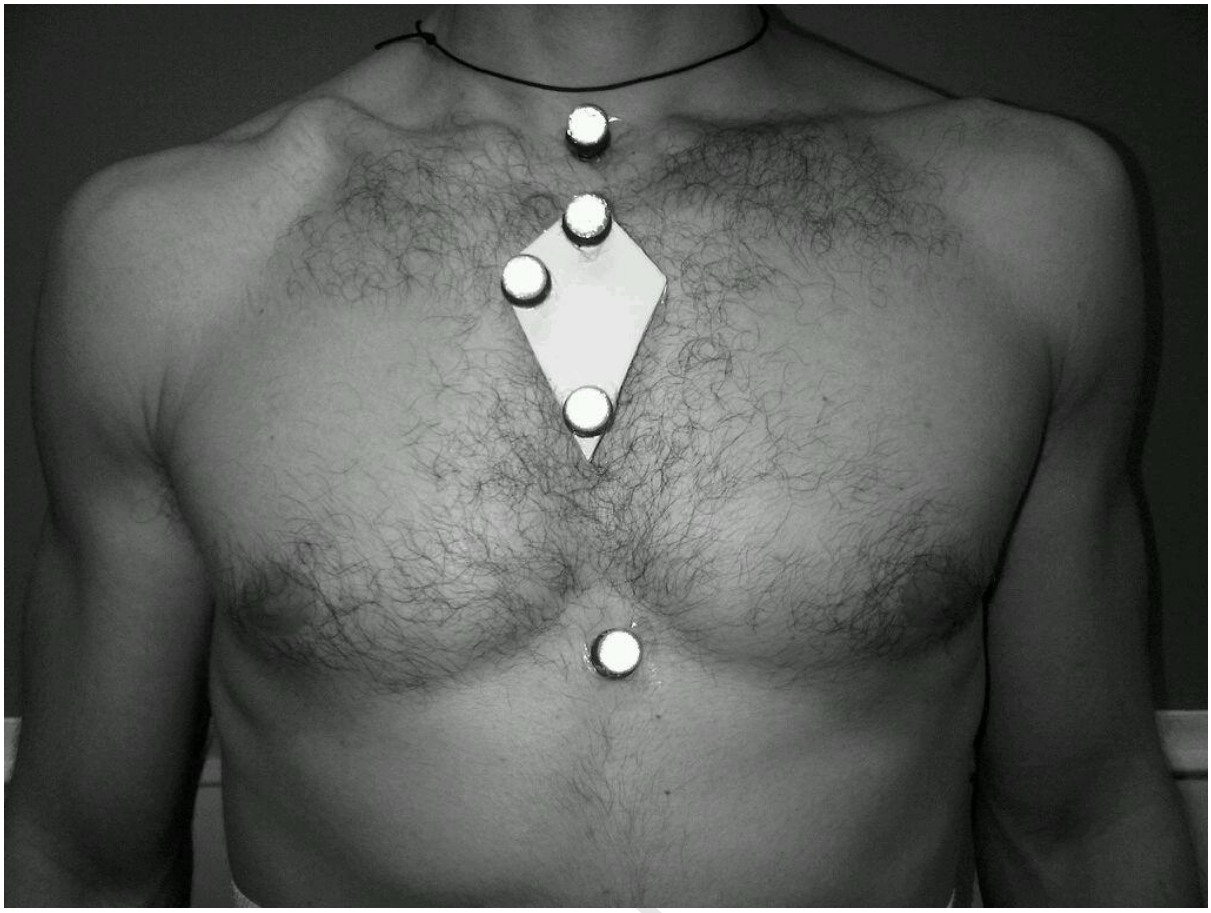

Figure 1b: Image of the marker set used to track the thoracic spine during running

- Good between-day reproducibility of thoracic spine with respect to pelvis in 3 planes
- Good between-day reproducibility of lumbar spine with respect to pelvis in 3 planes
- Good between-day reproducibility of thorax in lab coordinate frame in 3 planes
- Little difference between 6DOF and GO approaches for spine with respect to pelvis
- Motion of spine and pelvis in lab similarly reproduced in 6DOF and GO approaches