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Visualisation of dance performance using 3-dimensional motion tracking and muscle modelling techniques

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Abstract

Motion analysis and muscle modelling provides a 3D visualisation tool to demonstrate best practice dance techniques to enhance performance and reduce injury risk. Mental rehearsal of dance movements primes the musculoskeletal system and the use of imagery can assist in the recall of ideal movements prior to their actual performance.

Dancers practice or perform most days of the week and the literature has reported that heavy training, repetitive practice and any muscle imbalance adaptations may ultimately lead to injuries which affect approximately 70% of all dancers and can bring careers to an untimely and painful end.

Performance anxiety can tighten muscles and joints causing a decrease in focus and detract from optimal performance. It may also ultimately cause injury to the dancer.

3-dimensional kinematic and ground reaction force data provides an objective tool to visualise dance movements. The data provides a comprehensive analysis of positions of segments of the body, joint angles, joint angular and linear velocities and accelerations and the position of centre of mass which is not possible with descriptive kinematics.

Software has been developed in-house to calculate the muscle loadings and muscle timings in individual muscles within the dancer's whole body throughout the duration of any dance movement and has been configured specifically for use by dance teachers and students**.** The model consists of 666 muscle units, 36 anatomical segments and 35 joints and is animated using dancers' 3-D movement data. The output is presented as colour-coded graphics for visualisation of individual muscle activity and loading patterns.

Introduction

The human body is a highly sophisticated machine composed of a large number of components with an infinite number of positional configurations controlled by a wide range of internal and external factors. There is a complex interaction of physical forces acting on the body which the body must always contend with even whilst at rest.

Dancers have been described as a unique blend of artist and athlete and the physical demands placed on dancers make their physiology and fitness just as important as their skill acquisition and their ability to perform aesthetically. The extraordinary physical demands in performance of dance techniques have been compared to those placed on highly competitive football players (Teitz, 1983).

The prevalence of musculoskeletal injuries and pain in dancers has been reported as high (Hincapie, Morton and Cassidy, 2008) and international dance authorities have acknowledged there is a need to have a greater understanding of the effect of dance on the musculoskeletal system. Numerous chronic and overuse and injuries have been commonly reported due to the demands placed on the dancers' body whilst undertaking dance movements which might be beyond the dancers' capabilities and lead to musculoskeletal injuries and pain. The need to emphasise the importance of 'mechanical issues' has been addressed over the last three or four years and questions have been posed such as 'what fundamentally dictates how we dance?', 'what forces are responsible for dance movements?', 'what criteria dictates optimal performance?' and 'what are the mechanisms of injury?'

However unlike athletics and sports where the focus for the last two decades has been on quantitative analysis, research into the biomechanics of dance is suffering from growing pains and is still dominated by descriptive studies.

Three-dimensional motion capture is now a mature practice (Patrick, 1991) with proven benefits in clinical and sports environments in relation to improving performance and identifying injury mechanisms. The use of 3-dimensional motion analysis can now be found in the majority of dedicated clinical gait analysis facilities (Allard, Stokes and Blanchi, 1995) and biomedical engineers now routinely perform motion data capture and analysis which enables clinicians to apply the resulting information for the diagnosis and treatment of patients. Motion analysis provides a visual interpretation and an accurate measurement method of establishing normative gait parameters and for understanding pathological gait disorders (Cavanagh and Lafortune, 1980). The quality and validity of the data has enabled its use in pre and post operative evaluation (Perron, Malouin and Mcfadyen, 2000)

From its initial application within a clinical environment as a tool for analysing gait, the natural progression was research into the biomechanics of sports - running gait is a natural extension of clinical gait analysis (McGinley, Baker, Wolfe and Morris, 2009). The majority of research centred on the ground reaction forces exerted against the runner's shoe sole and its affect on running mechanisms. It provided athletes and coaches with a more objective tool to analyse running gait in relation to improving performance and offered a more comprehensive analysis of positions of the segments of the body, joint angles, joint angular and linear velocity, joint angular and linear accelerations and the position of centre of mass which was not possible with descriptive kinematics.

Other sports soon became a target for research and a number of studies used 3-dimensional optical tracking to record the kinematics of movement to provide accurate and objective data; for example, weight lifting (Lauder and Lake, 2008), throwing events (Nissen, Westwell, Ounpuu *et al.*, 2007), wheelchair tennis (Reid, Elliott and Alderson, 2007), cycling, rowing and track and field events (Tilp, Wagner and Muller, 2008).

Visualisation is an important technique in dance practice. Mental rehearsal of dance movements primes the musculoskeletal system and the use of imagery by the dancer can assist in the recall of performing the ideal movement prior to the actual movement. However feedback from the mirror in a dance training environment is only one method of detecting and correcting movement patterns and research in the field of motor learning provides insufficient evidence that movement corrections based on visual feedback obtained from the mirror can be used in the context of dance performance (Magill, 2001).

An effective method of learning new dance skills and movements has been for the teacher to demonstrate dance movements. However teachers must be assured that they are providing both clear verbal instructions and descriptions together with a precise visual image of the movement. They must also be certain that students are perceiving the movement accurately and are not focussing on aspects which are of less relevance to the whole movement. However the development of a 3-dimensional animated computer model of ideal dance movements is a tool which can support teaching and learning.

3-dimensional movement analysis enables dancers to visualise their posture and quantify precisely how each segment of the body contributes to the whole movement. (Figure 1) The musculoskeletal model of the dancer can be viewed from any direction and at any speed which enables dancers to totally familiarise themselves with the correct actions in order to maximise their technique and minimise their injury risk.

However dancers cannot see the forces affecting that motion i.e. gravity, friction, muscle tension and external resistance. To understand these factors it is necessary not only to analyse the kinematics of movement, which provides a comprehensive description of the movement, but also the kinetics which gives information regarding the forces acting on the body. 3-dimensional motional analysis of the dancers' movement alone cannot directly reveal the external loading pattern and magnitude within the dancers' bodies which may results in injury; however it is possible to calculate these forces given information on anatomy and muscle physiology.

Performance anxiety can also make the body tense, tightening muscles and joints which can lead to a decrease in focus, may detract from optimal performance and may also ultimately cause injury to the dancer. There are many explosive movements in dance which require muscular strength and measurement of the dancers' movement alone cannot directly reveal the external loading pattern and magnitude within the dancers' bodies which may results in injury, however it is possible calculate these forces given information on anatomy and muscle physiology.

Consideration of the dancers' soft tissue, e.g. muscle, is significant for performance, injury avoidance and aesthetics. The assumption is proposed that injury risk associated with a muscle and a joint is a function of the load within the structure and that an increased load will increase the injury risk (it is acknowledged that the risk is also a function of other factors, e.g. frequency of loading, duration of loading, pose during loads etc.).

There was a view that non-dance exercise training would diminish the aesthetic appearance of the dancer (Koutedakis, Stavropoulos-Kalinoglou and Metsios, 2005); however the counter-argument is that stronger core muscles equals a stronger dancer. For example, it was reported that strong latissimus dorsi muscles in the mid to lower back would make partnering safer for both men and women dancers and prevent lower back injury (Thompson, 2008) and investigations of dancers’ thigh strength in relation to lower extremity injuries indicated that the lower the thigh strength levels the greater the degree of injury (Koutedakis, Khalouha and Pacy, 1997).

However a review of literature has identified that any quantitative data regarding the forces which can be generated in human muscles is extremely limited and any data specifically regarding dancers is non-existent. However in order to make better informed decisions based not only on the requirements of the aesthetics of the dance but also on the design of dance performance, training techniques and the continuing health of the dancers, it is suggested that dancers, teachers and their healthcare practitioners should have a knowledge of muscle forces and loading impact of particular dance steps. For example, a knowledge of how much force was required to undertake specific dance movements would enable the dancer’s performance and dance technique to be optimised without the risk of potential injury.

However in order to be able to calculate the muscle loadings and muscle timings within the whole of the dancers’ bodies it was necessary to develop muscle modelling software. This would enable dancers to visualise and identify muscle loadings and muscle timings throughout the duration of any dance movements.

The muscle appearance can illustrate various properties of the muscle strength, force or activations throughout the dance movement and for ease of visualisation the graphics developed for the software show these as muscle thickening (bulging) as more force is applied or by the change of muscle colour. The colours range from blue, through to green, yellow and red as the maximal which equates to the maximum stress which can be generated by the muscle. The muscle model is driven by the processed 3-dimensional motion data.

In order to calculate the muscle loadings and muscle timings acting between the segments of the body, it was necessary to identify the physiology of the muscles and their corresponding anatomical positions. The model included the x, y and z co-ordinates of the muscles’ origins, insertions and wrapping points on the body segments together with force data for each muscle of the body. Muscles were modelled as force generators acting between their respective origin and insertion points. Muscles which wrapped around intermediate anatomical locations were also modelled. For example, biceps femoris has an origin on the pelvis, wraps around the femur and inserts into the tibia. Individual muscles may have many parts that function in different ways, for example the deltoid muscle. The anterior deltoid is involved in shoulder abduction when the shoulder is externally rotated; the posterior deltoid is involved in transverse extension and is the primary shoulder hyperextensor and the lateral deltoid is involved in shoulder abduction and flexion when the shoulder is internally rotated and transverse abduction when the shoulder is externally rotated. The model consisted of 666 muscles units for 198 individual muscles.

A muscle's force generating ability is a function of its physiological cross-sectional area (PCSA) (Brand, Pedersen and Friederich, 1986). PCSA at optimal muscle length was defined as the muscle volume divided by the optimal fiber length, where muscle volume was defined as muscle mass divided by its density (Breteler, Spoor and Van-Der-Helm, 1999). Muscle strength was used to indicate the maximum tension a muscle was capable of producing per physiologic cross section. The majority of literature reviewed reported a strong correlation between the cross-sectional area of a muscle and the maximal force that a muscle could produce i.e. the larger the physiologic cross-sectional area of a muscle, the more tension it could produce (Lehmkuhl and Smith, 1988).

The literature reviewed also identified there was quite some disparity in the quoted PCSA figures which were used to calculate the maximal force that a muscle could produce. Von-Recklinghausen reported the strength to be 36N/cm^2 (Von-Recklinghausen, 1920); and Haxton suggested the absolute muscle strength of the plantar flexors of the ankle to be 39N/cm^2 (Haxton, 1944). Wirhed stated that a muscle can develop a maximal force of about 50N/cm^2 (Wirhed, 1997). The maximal force used within the model was 31.8N/cm^2.

However it is impossible to predict the PCSA for each muscle for every individual human and therefore it is important to appreciate that the PCSA identified in the muscle model is indicative, not an absolute expression of the relative strength of each muscle or muscle group. The relationship between cross-sectional area and muscular strength can only be estimated as cross sections of muscles vary considerably between individuals but the cross-section of a muscle can be an indication of the relative strength of each muscle or muscle group. However there appears to be a strong correlation between the cross-sectional area of a muscle and the maximal force that a muscle can produce. The larger the physiologic cross-sectional area of a muscle, the more tension it can produce.

Method

The dance movements of twenty-two professional ballet and Irish dancers were captured using a 12 camera 3-D Vicon MX 40 optical tracking system utilising Nexus as the operating system (Vicon). The dancers undertook a range of dance movements which were indicative of their dance performance and practice. A protocol of twenty five dance movements were compiled by professional ballet school instructors, for example, sauté de Basque, fouette, grand rond de jambe, arabesque, ciseaux jeté and grand pirouette and a similar protocol of dance steps was compiled by a World Champion Irish Dancer including jigs, impact steps, trebles, counter-steps and stamps. The means and variance amongst the dancers of the data are analysed for the range of the codified dance movements.

The subjects gave informed consent and the study was approved by the University's Research Ethics Committee.

The articulations of the joints in the musculoskeletal model was driven using the motion data. Thirty seven retro-reflective markers were attached to the dancer at anatomical landmarks which could represent the whole body movement of the subject (Figure 2). The dancers performed on a 4 metre by 4 metre Harlequin sprung floor (Harlequin) into which were mounted 2 AMTI OR-6 forceplates to measure the ground reaction forces (AMTI). The motion data was recorded at 250 frames per second and 12 channels of ground reaction data was recorded at 2000 samples per second. Measurement accuracy of less than 1mm in a 4m x 4m x 4m volume was achievable.

The data from the optical tracking system was used to calculate the joint range of motion of each of the professional dancers and provided a comprehensive analysis of positions of the segments of the body, joint angles, joint angular and linear velocity, joint angular and linear accelerations and the position of centre of mass which is not possible with descriptive kinematics.

For calculation purposes an assumption is made that the retro-reflective markers are attached to the dancer's skeletal segments whereas in reality the skin moves over the underlying skeleton which introduces errors into the calculations. These errors were reduced by attaching the markers to bony landmarks e.g. the epicondyles, where movement of the skin is smaller than at other locations.

Having recorded the location of the markers attached to the subject, the joint articulation time histories were calculated and expressed as moving axis Euler angles using a BodyLanguage routine which was written for this study. Cubic interpolation splines were fitted to the recorded articulation data ensuring continuity in the angular second order time derivative.

The motion data and the forceplate data was input into the developed biomechanical modelling system to calculate the muscle activations for each of the dancers. The model consists of 31 segments representing the major anatomical components (head, thorax, pelvis, upper/lower arm, hand, upper/lower leg, foot, scapulae, clavicles, 7 cervical and 5 lumbar vertebrae).

The mass distribution and inertia properties of the segments were obtained from Hatze (Hatze, 1980).

These segments were connected with 35 joints. The joints were of the forms which model the function of the anatomical counterpart, e.g. a spherical joint for the hip joint, a hinge joint for the elbow, a 2-axis cylindrical joint for the ankle, a slide joint for scapula/thorax, a roll/slide joint for the knee.

The body of the dancer is assumed to be composed of a number of rigid segments, each with associated mass and rotational inertia properties. These segments are interconnected by joints. Forces act between these segments due to muscles which cross one or more joints. External forces, for example ground reaction forces, act on the dancer. For this study, generalised co-ordinates predominantly represent the articulation of the dancers' joints and the generalised forces are predominantly the torques at the corresponding joints. Muscles were modelled as force generators acting between their respective origin and insertion points and muscles which wrapped around intermediate anatomical locations were also modelled. For example, biceps femoris has an origin on the pelvis, wraps around the femur and inserts into the tibia.

The torques at the joints due to inertial forces and external loads are in dynamic balance, in accordance with d'Alembert's principle, with the torques generated at the joints by the muscles traversing the joint (Lanczos 1970. However there is not a unique solution for this system as the number of muscles is greatly in excess of the number of joints and hence the number of torques. Therefore it is necessary to select the one solution for the infinite possible solution which minimises an optimisation function. Numerous optimisation functions have been proposed (An, Kwak, Chao, and Morrey, 1984) (Gracovetsky, Farfan and Lamy, 1977), for the current study, the sum of the square of the muscle activations is minimised where muscle activation is defined as the muscle force divided by the muscle maximal isometric load. The optimised solution must also satisfy a set of equality conditions (the external torques due to external forces and segmental inertial forces must equal the torque due to the surrounding muscles at each joint) and inequality conditions (the load in each muscle must be positive as the muscle cannot push and the load must be less than the maximum force the muscle can generate).

All of the mathematical models and analysis code utilised in this study was developed in Matlab® (The MathWorks Inc™).

Results and Discussion

After undertaking the 3-D motion capture the resulting motion data was provided to the dancers in a format which could be readily visualised and understood in order to advance their knowledge and implications of the effect of dance on the musculoskeletal system. The 3-dimensional motion data of the musculoskeletal system could be viewed at any speed and from any angle. The individual muscle activations/timings together with joint torques utilising the developed modelling system was also provided to the dancers to enable them to visualise the forces acting on their bodies during the dance movements.

The dancers reported that the retro-reflective markers and targeting of the forceplate did not have a detrimental effect on their performance of the various dance movements.

Although the professional ballet and Irish dancers undertook a range of dance movements, only one is reported here and is used as an exemplar of the analysis and visualisation techniques which can be achieved using motion analysis and muscle modelling.

The Irish dancers were asked to perform a wide variety of movements including the Rock step. "The Rock" is unique to Irish dance where the dancer synchronously inverts and everts both ankles whilst on the balls of the feet so that one ankle is pushing the other ankle and the dancer rocks from one hallux to the other hallux. Anecdotal evidence suggests that the Rock is responsible for numerous ankle joint and soft tissue injures. A video of the movement and the muscle activations can be observed at www.marlbrook.com/animations/edel_Rocks.avi (1.6Mb file).

Although dancers can see their movement they cannot see the forces acting on their muscles and joints. Figure 3 is an illustration of the musculoskeletal model for a representative dancer in an arbitrary posture of The Rock and illustrates the activation of each muscle represented by a bulge which is a function of its state of activation. The colour of the muscle is also representative of its activation; from blue, through to green, yellow and red as the maximal activation.

The Achilles tendon is prone to overuse injuries and studies have shown differences in kinematics with greater eversion, ankle dorsiflexion and knee flexion. The mechanical loads within the Achilles tendon and the attached soleus and gastrocnemius muscles were analysed during the Rock. It was noted that the highest force levels in the gastrocnemius muscle was 2510N compared to 1495 in the soleus and hence the Achilles tendon was 4005N compared to 500 – 1430N for walking (Finni, Komi and Lukkariniemi, 1998). (Figure 4)

The forces in each of these muscles was normalised to the muscle's maximal isometric load, which is its activation and are illustrated in Figure 5. An activation of 1.0 indicates that the muscle is operating at its maximal isometric force. The maximum activation of gastrocnemius is 1.6 although this occurs for a very short duration. This indicates that the muscle is operating at higher than its maximal isometric strength. It has been shown that muscles can generate forces in excess of their maximal isometric force for brief durations of time (Kawamori, Rossi, Justice et al., 2006). The next highest activation is 1.06 and 0.96 indicating that the muscle is operating at approximately its maximal isometric strength.

It was also calculated that ankle contact forces during the Rock were 14 times body weight and, coincidently, it has been established that ankle forces during running are approximately 14 times body weight (Edwards, Thomas and Derrick, 2007) (Figure 6). Therefore it is concluded that the joint contact force at the ankle during the Rock is comparable with the loading at the ankle during running.

The ground reaction forces acting between the feet of the dancers and the floor were also calculated and normalised to the weight of the respective dancer. The peak ground reaction for all dancers taking part in the study is in excess of 2.5 times bodyweight during the Rock, with one dancer achieving over 4.5 times body weight.

Figure 7 illustrates the contact force between the tibia and talus as double headed arrows. The length of the arrow is indicative of the load and the direction of the arrow is aligned with the resultant direction of the contact force. A video of the joint contact force system throughout the body can be observed at www.marlbrook.com/animations/all_forces.avi (2.2Mb file) and www.marlbrook.com/animations/all_forces_back.avi (2.5Mb file).

Conclusion

This paper addresses the benefits that motion analysis and muscle modelling can offer to the dance community as a 3D visualisation tool to enhance performance, demonstrate best practice dance techniques and reduce the risk of injuries.

Many aspects of movement are difficult to describe verbally and teachers have to be certain of the accuracy of their demonstrations. With the advent of modern 3-D motion capture equipment, analysis software and muscle modelling techniques, the range of movements, flexibilities and muscle loadings for dancers across a range of ages and abilities can be seen. This offers teachers an alternative and creative teaching tool and could make the learning process more engaging and motivating for the students.

Although mental rehearsal of dance movements primes the musculoskeletal system, the use of dynamic visual imagery by the dancer can assist in the recall of performing the ideal movement prior to the actual movement. The output from the motion analysis enables dancers and teachers to visualise in three dimensions exactly what is happening to each segment of their bodies as they perform various dance movements and assist with their understanding of how the constituent parts interact to contribute to the whole movement. It also enables any movement errors which may be present to be detected and corrected.

Although the 3-D motion analysis provides dancers with an understanding of the kinematics of their movements, the muscle model which has been developed enables dancers to visualise and identify the muscle loadings and muscle timings throughout the duration of any dance movement. The graphics developed for the modelling software illustrates the various properties of the muscle strength, force and activation by changing colour and thickening (bulging) as more force is applied.

The information provided by the motion analysis and muscle modelling will not only improve dancers' performance but also help reduce the risk of injuries which may occur when undertaking movements which are inappropriate either for their level of ability or maturity.

The analytical information is not only of benefit to the dancer or dance teacher. It can also be used by their clinician or physiotherapist in determining a suitable rehabilitation regime in the event of a muscle imbalance or injury. For example, a dance movement which is seen to highly load a part of the body which is recovering from an injury might best be avoided whereas an activity which repeatedly lightly loads a recovering anatomical region may be recommended. This will prove invaluable to dancers in terms of being able to make informed decisions based on their new knowledge of the loading impact of particular positions and steps and consequentially will enable the dancers to develop choreography that prevent injury.

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Figure 1 *Motion tracking of segments of the body during a pirouette*

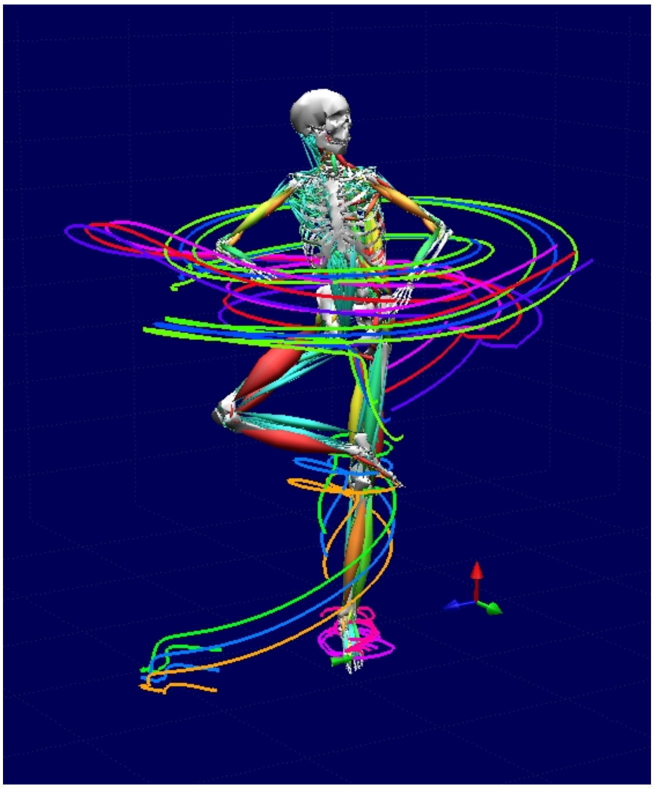

Figure 2 *Retro-reflective optical tracking markers attached to a dancer*

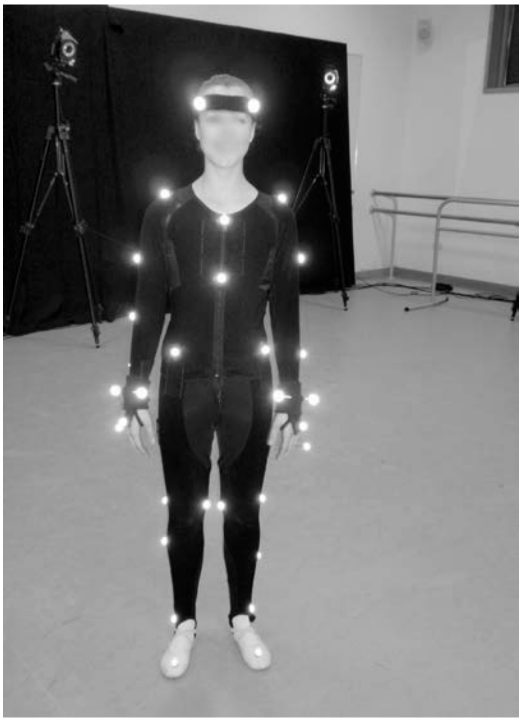

Figure 3 *Muscle load distribution - the shade of grey of the muscle is indicative of the force generated in the muscle*

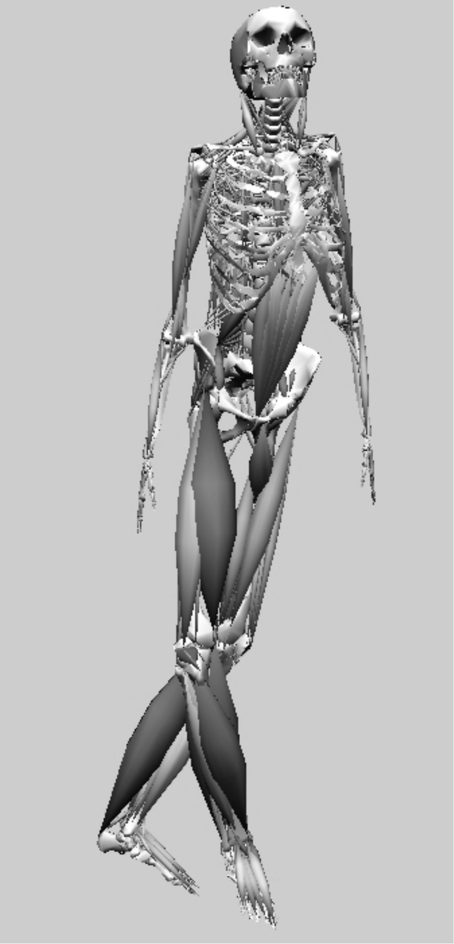

Figure 4 *Forces in muscles attached to the Achilles tendon during the Rock*

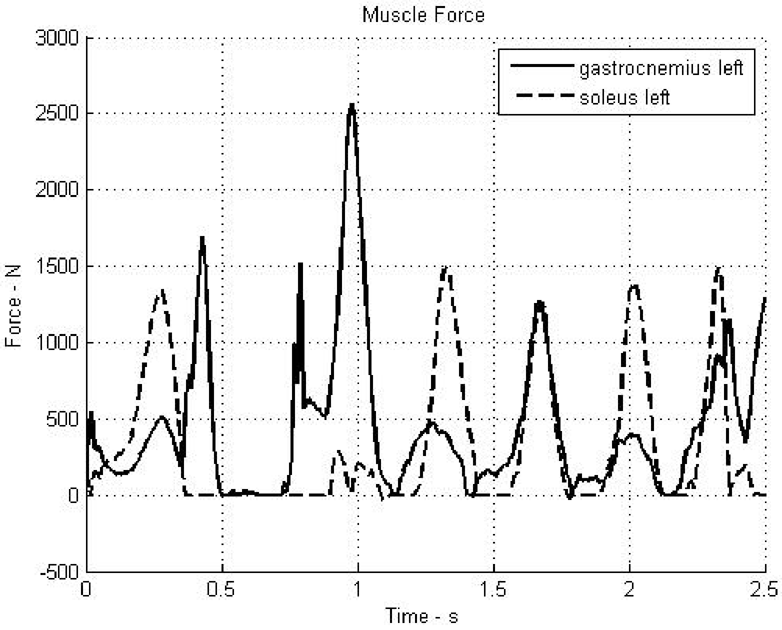

Figure 5 *Activation of muscles attached to the Achilles tendon during the Rock*

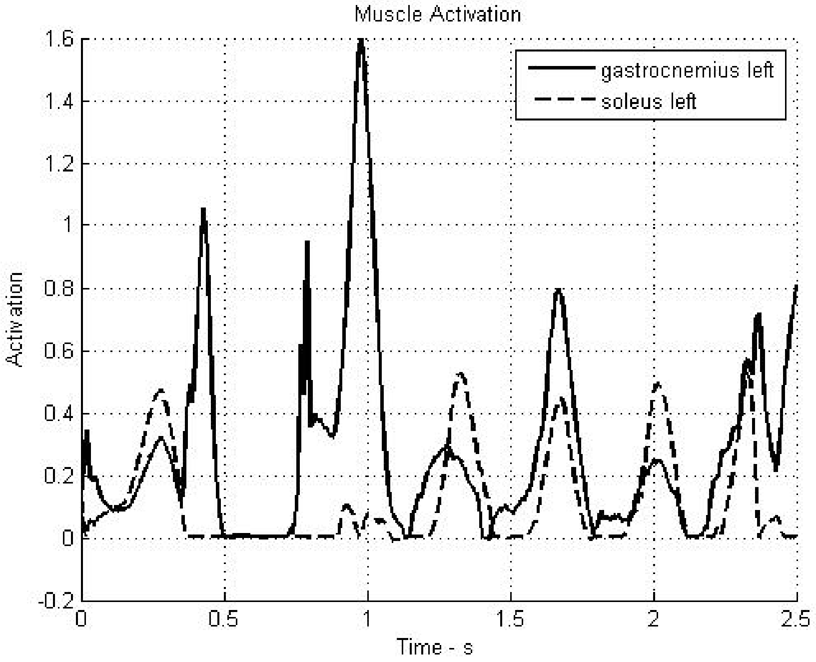

Figure 6 *Plot of ankle joint contact forces during the Rock normalised to body weight*

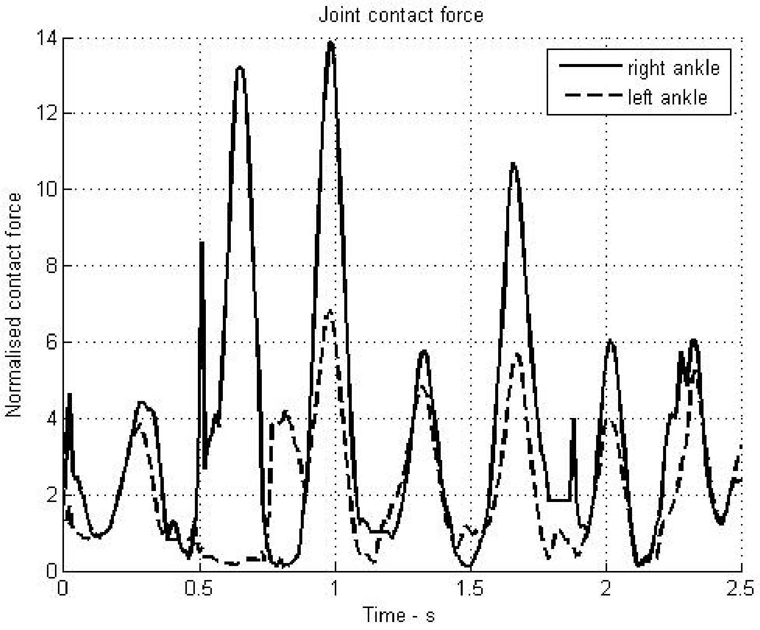

Figure 7 *Instantaneous ankle joint force during the Rock; the length and direction of the double arrows is indicative of the internal forces acting at the ankles*