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A SPINNING-HULL APPROACH PROVIDING RAPID BALANCE CALCULATIONS WHEN MODELLING HUMAN POSTURES

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1. Introduction

When studies are undertaken into the postures of humans using computer models it is often a requirement to establish whether the manikin is in balance.
In trying to determine the balanced state it is necessary to establish whether its centre of gravity lies within the base of support that lies within the feet of the manikin. For a stationary model, the position of this centre of gravity is readily found by taking moments of the individual body part masses about a reference point. The position of it with regard to the contact area of the feet, defined as its convex hull, will show whether the model is in balance or not. This is, however, complicated when movement of the body parts and limbs occur which effect both the position of the centre of gravity and, if the feet move, also results in changes in the resulting convex hull. Such problems occur particularly when a movable manikin is being considered in which the required action needs to result in limb movements to both provide balance, and to undertake a desired action, such as the holding, or pointing at, an object. These problems can exist, for example, during the study of a manikin walking up stairs. This can result in an increase in computation due to the number of balance frames required, and the repositioning of the manikin that occurs between each attempt (Figure 1).
In this study the manikin is seen initially standing and looking at the stair (Figure1(a)), with balance needed to be achieved between the feet. Immediately before the lifting of one foot from the ground the centre of gravity must be moved across into the hull of the other foot (b) so that the first leg is free to rise (c). The rising leg is then swung over the step (d) before being planted down (as seen in the final image (e)).At this time the balance is maintained by ensuring that the centre of gravity (shown as the blue vertical line) lies within a convex hull that encompasses both feet. The changes of the feet positions result in different forms of convex hull being generated at each instance, that can be further complicated if hand rails and the carrying of objects are also included.
Such combined movements result in the possibility of a large number of iterations when balance is sought, and hence extensive computing times, if conventional convex hull calculations are employed. The aim of this paper is, therefore, to create a fast and simple approach that can be integrated within a direct search balance routine, which can be employed in a constraint resolution approach.

2. Human modelling

A constraint modelling environment was created at the University of Bath for use in the solution of design problems. In this the design is expressed in terms of rules that must be true if the problem is solved [Medland 1996]. Solutions are found by direct search techniques of the declared design variables, based upon a modified Hooke and Jeeves method [Hooke 1961]. This approach has been

employed in a wide range of design studies that have included mechanisms and medical equipment and, in particular, the design of packaging machinery [Matthews 2006].
For its application to human posture studies an extensive human modelling capability was created and incorporated within the environment [Molenbroek 2000]. This now includes the ability to embed and pivot separate body spaces, the application of restricted numbers of degrees-of-freedom, and limits on the rotations between them. The solution is found by an advanced direct search technique with the search variables selected by an extended sensitivity analysis approach [Medland 2011]. Finally, the problem being addressed can be changed by the rules being switched on and off, or the creation of new ones.
The balance of the manikin within the environment is calculated from an array of body part masses, as obtained by Dempster [Dempster 1955]. These need to be recalculated, at each posture, as the arms and body positions may change during a search for a new balance state.

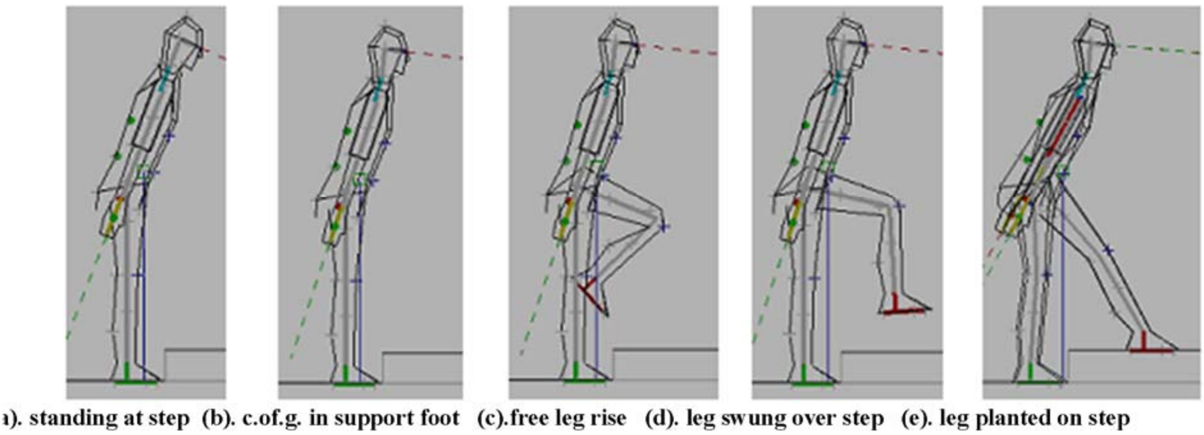

Figure 1. The starting movements of a manikin climbing up a step

3. Studies of balance

3.1 Methods of calculation of convex hulls

When a number of points are projected down onto a ground plane, to represent the points of contact for balance, the centre of gravity must lie within the minimum shape that encloses all of these points. This is known as the 'convex hull' and is often described as the elastic band that tightly encloses all of the points [Wikipedia 2011]. In so doing the 'band' touches the furthermost points and simply encloses the remaining inner ones.
There are many ways by which the convex hull can be calculated. The most commonly used are based upon making a guess on the form of the hull by selecting three points to form a triangle, and progressively expanding the side by the selection of points that are outside of the guessed solution, until all points are contained within the minimum number of edges. This is commonly termed the 'quickhull' approach but does require extensive searching.
Another, called the 'divide and conquer algorithm' commences, not with a single triangle, but by splitting the points into two groups, usually in one of the axis directions. These two groups are checked and individual hulls formed, or systematically reduced, until more hulls are established. They are then drawn back to form a single hull by finding edges that touch the extremes of each original hull (without crossing into either of the test hulls). This also results in a large number of iterations.
Yet another method, referred to as 'gift wrapping', selects an edge at random and searches to see whether there are any points on the outside (or to the right). If there is, the furthermost is chosen and the edge is replaced by one drawn to this new point. The process is again repeated until a hull is created by circulating, in say, an anticlockwise direction, to encompass all the points and returning to join up with the original starting edge.

Whilst all of these methods have been used to create a chosen convex hull in the constraint modeling environment, they do require both repetitive calculation, and geometric analysis, which can make them slow to use within a direct search procedure, especially when the search may need to be repeated many times before a true and balanced solution is found.

3.2 A spinning approach to convex hull generation

An approach, here referred to as the 'spinning hull', is related to the bounding box work of Chang, Gorissen and Melchior [Chang 2011]. This has been specifically created for use in balance calculations and has both used and extended the bounding box approach.

3.3 Bounding box

The bounding box is formed by determining both the maximum and minimum values of the set of hull points in each orthogonal direction. The box is then generated with edges in these maximum and minimum directions, as shown in figure 2, which will then just contain the true convex hull (shown in red) but will encompass a slightly larger area.

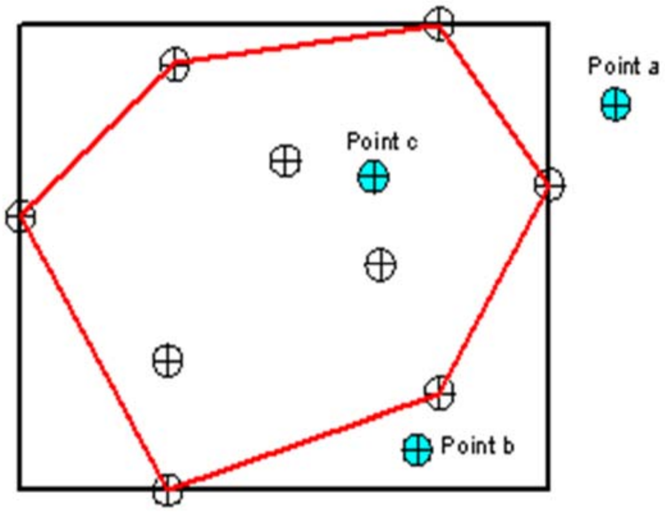

Figure 2. Convex hull (in red) and bounding box

If the centre of gravity for the manikin is calculated, and is found to occur outside the bounding box (as for point 'a') it will also be outside of the convex hull. Alternatively, if the point is inside the bounding box it is not guaranteed to be inside the hull (as is point 'b') and further tests need to be undertaken (such as are used in the previous methods for hull generation) to establish that it truly lies within the hull (as for point 'c').

3.4 Constraint modelling environment

However, in the constraint modelling environment, a number of features and functions are included that aid the generation of this type of hull method. The first is the built-in function to determine the maximum and minimum values in a set of values. The coordinate values can also be automatically stripped from each point thus allowing the rapid generation of the bounding box condition.

An additional feature of the constraint modelling environment is that all geometry is embedded within a model space (either collectively or individually). These spaces, in their turn, can be embedded within any other model spaces with each having nine degrees-of-freedom (three of translation, three of rotation and three of scale). This allows bounding boxes to be created in multiple spaces that are rotated incrementally about a reference space.

When the rotation is set at a sufficiently fine interval (usually at 5 degrees for human modelling conditions), it is then easy to determine that the convex hull is the swept space of the minimum configuration of all the bounding boxes. However, if the centre of gravity is shown to be outside that of any of the generated bounding boxes, then the centre of gravity point is outside the true convex hull (as shown by the three points in Figure 3).

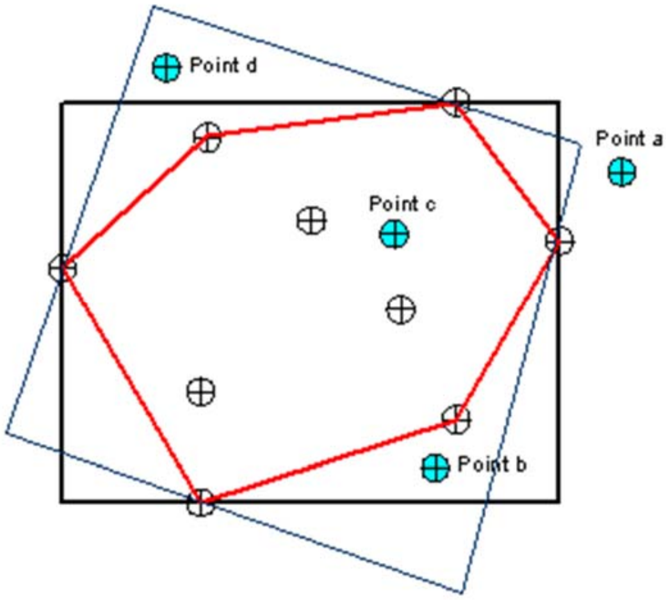

Figure 3. Centre of gravity points around the hull

Having spun the set of bounding boxes and determining whether the chosen centre of gravity point is inside or outside the bounding box, then only the following test needs to be undertaken:

If the point is found to be OUTSIDE of ANY of the boxes then the point is OUTSIDE the hull

If, however, the point is found to be INSIDE of ALL of the boxes then it is INSIDE the hull

This provides a simple and quick way of establishing whether the hull test is valid and the search can be terminated as soon as this is established (Figure 4).

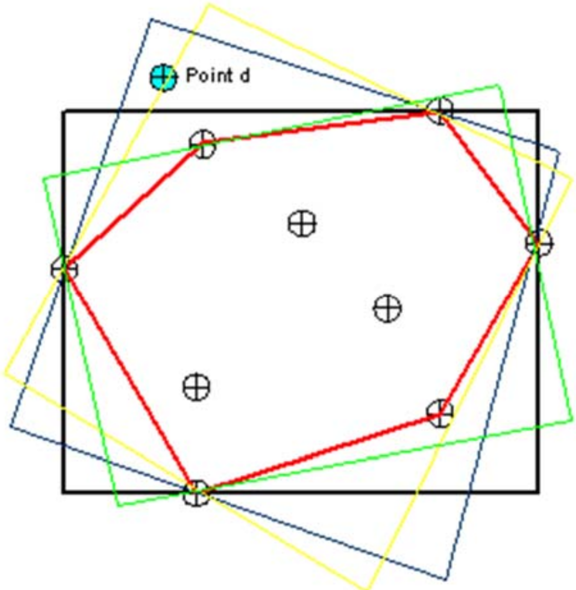

Figure 4. Multiple bounding boxes to create convex hull

Care must obviously be taken to ensure that sufficient rotational angles are taken in the search to capture all points within the search. In its use in seeking human balance the contact points of the foot with the ground are set within the full spread of the foot to allow a spinning angle as high as 5 degrees to be used successfully.

4. Examples of manikin applications

Studies using the constraint based manikin will often require that the posture of the manikin is checked for balance through the use of convex hull calculations. This will arise in many forms, some of which are illustrated in the following sections.

4.1 Two footed balance

Two footed balance is often the initial starting state required before other actions take place as is the case with the stair climbing example shown in Figure 1. In this, and the close up shown in Figure 5, the manikin is required to stand by rules that ensure the three contact points, on each foot, are in contact with the ground. In the constraint modeller any rule is true if it equates to zero. This is thus achieved by each free variable of the manikin being manipulated until all the rules governing the standing are true. In doing this the sensitivity analysis initially seeks which variables dominate the solution (which in this case is mostly the vertical position of the manikin). These variables (the height and a few others governing the tilt of the body) are then manipulated in the direct search approach until the total of the rules equate to zero and the manikin is seen to be standing on the ground.
As the three contact points on each foot are chosen to represent the big toe, the little toe and the heel, the manikin is seen to be balancing on a triangle set within the sole of each foot (this also ensures that the contact is calculated well within the foot width).
The centre of gravity is then calculated from the body segments derived by Dempster [Dempster 1955] and scaled for total body mass. This position is projected down to the ground level, and is seen in Figure 5 as the blue upward, red left and yellow forward pointing arrow positioned, in this example, to the rear between the feet.

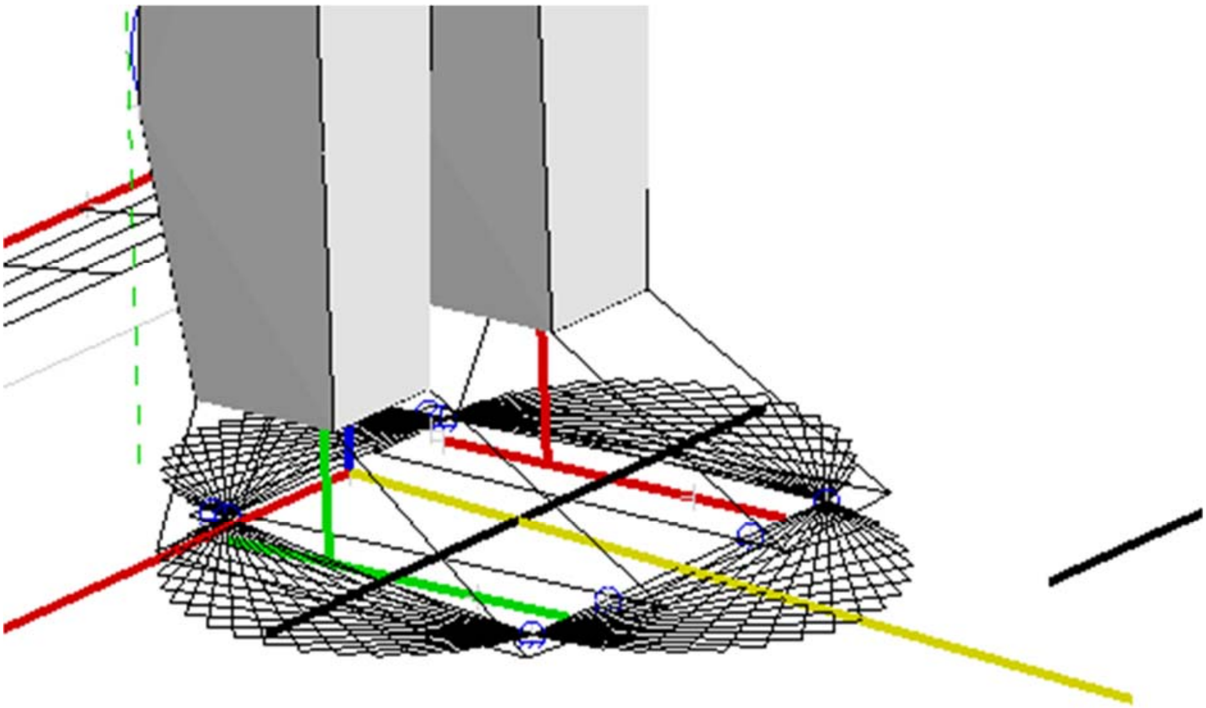

Figure 5. Spinning hull construction around two feet

The spinning hull calculations are then performed, in this case, at a rotation of 5 degrees, to create the inner hull. Due to the centre of gravity point being inside all of the spinning bounding boxes a balanced state is returned.

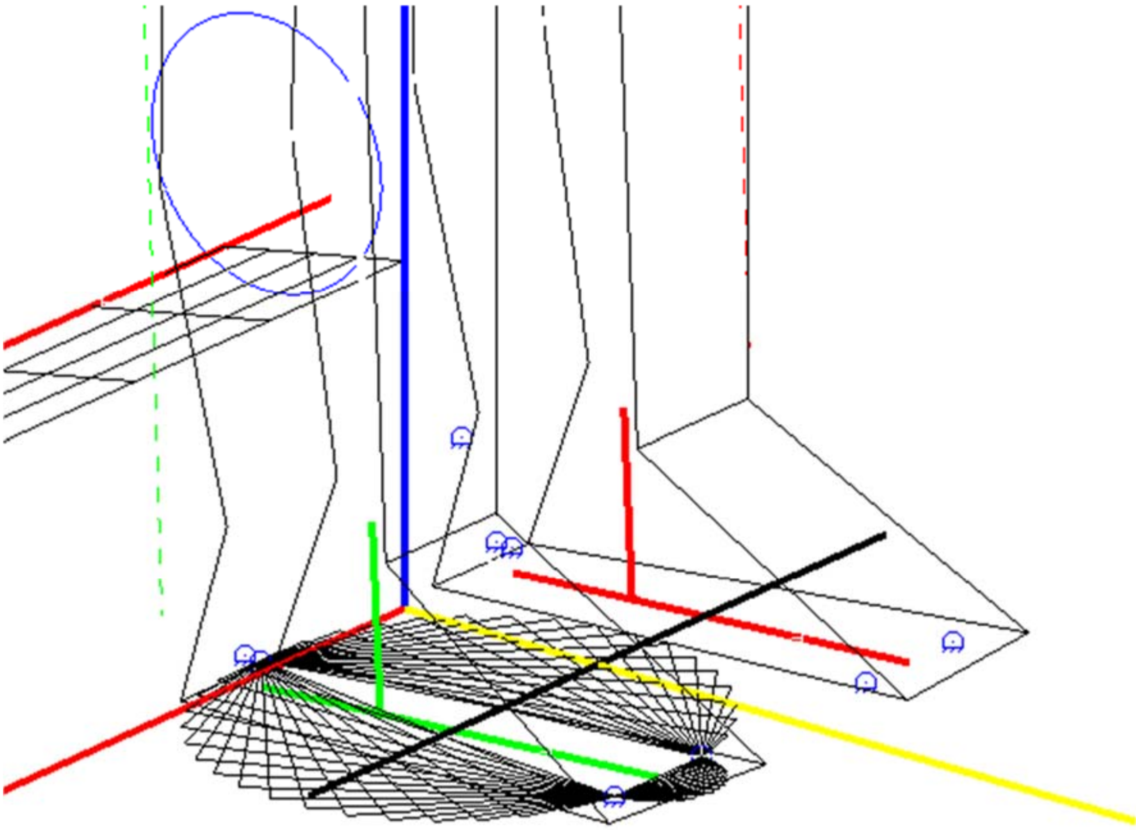

Figure 6. Hull construction around single foot

4.2 One footed balance

Once one of the feet is not in contact with the ground, as is required in state (b) in Figure 1,by no matter how small an amount, the convex hull needs to be regenerated around the remaining contact foot as shown in Figure 6.

In this study the remaining contact points are the three associated with the right foot, which then results in the triangular hull as shown. The centre of gravity point is now seen to be outside of the hull and an unbalanced state is reported.

To re-establish balance the manikin has to be disturbed by the movement of the upper body and the arms with a balancing rule included as well as that for contact . The result of such an investigation is shown in Figure 7 where the search has been seen to be performed with the majority of movement being undertaken in the upper torso and both shoulders. The balance vector is then seen to pass through the sole of the right foot close to the ankle. However for further stair climbing the manikin is required to lean more heavily to the left and raise the head into a more preferred walking posture.

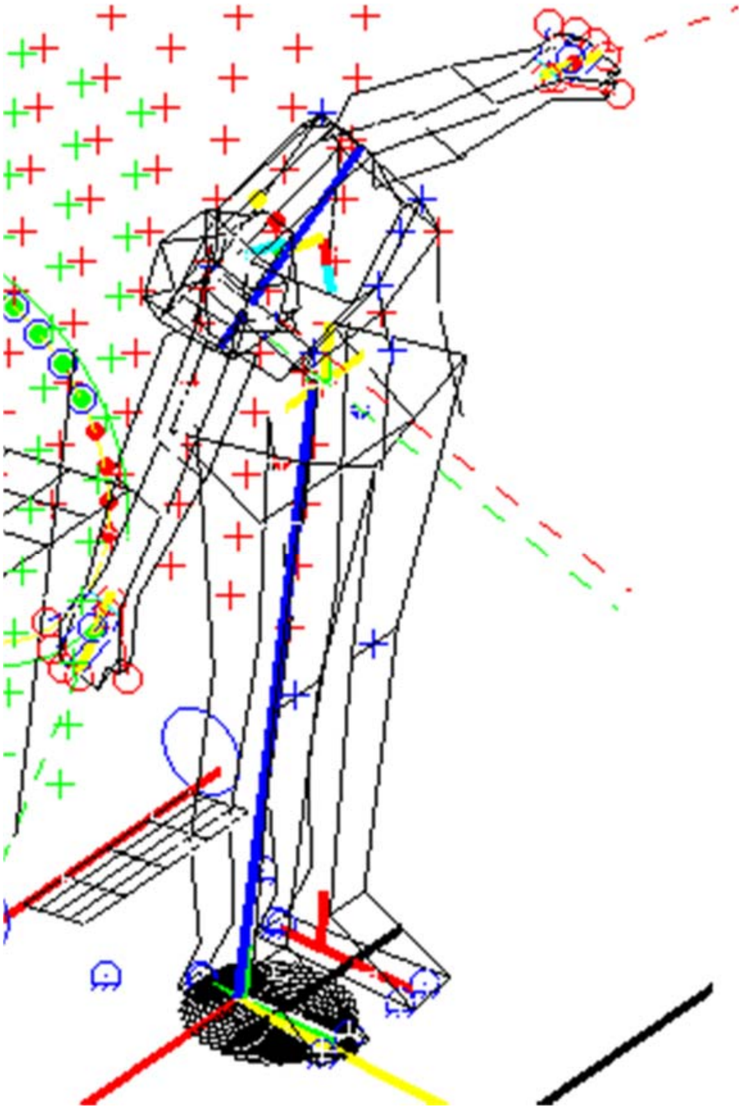

Figure 7. Manikin shown to be in balance when standing on the right foot

4.3 Climbing up a single step

The final example related to the stair climbing study, the manikin is seen in posture (e) climbing a single step with the left foot raised, and in contact with its surface. The convex hull is then constructed on the ground plane, and includes the raised foot contact points that are also projected onto the ground (as shown in Figure 8).
Once this convex hull has been generated, a search and manipulation of the body parts can commence to move the centre of gravity into the space.

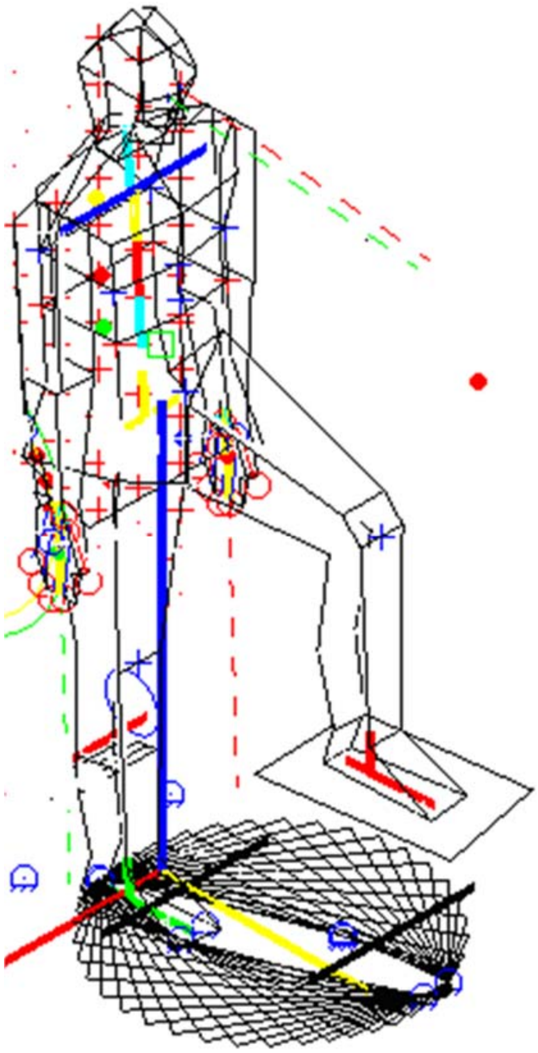

Figure 8. Manikin shown climbing a step with both feet in contact and the hull projected onto ground

4.4 Sitting in a wheelchair

A final example, as shown in Figure 9, is that of a manikin sitting in a wheelchair. This has been used in an extensive study of manual wheelchair design [Gooch 2008]. Here two studies of balance need to be considered. The first being the ability of the subject to remain seated in the chair and the second for the chair to not topple over then it is being moved.

The constraint rules imposed for the sitting condition require the manikin to contact the chair through the buttocks points, lean against the chair back, place the feet on the foot rest whilst being able to reach and push the driving wheels. Due to different types of spinal injuries and strength tetraplegics will take comsiderable different sitting postures that, range from being slumped well back, to that of leaning forward.

Similarly their posture in the seat will effect the balance of the complete chair which must, in its turn, be studied.

The posture of the manikin for individual cases, is found through the application of a number of embedded rules supported by an experimental investigation. These rules included, as before, contact with the seat, leaning back, and feet on the footrest and hands on the wheels, together with a rule requiring the combined centre of gravity being within the convex hull of the resulting wheelchair. In Figure 9 the posture is seen to be within the hull that encompassing all the points of contact including the buttocks and the feet. Here the centre of gravity is seen to lie within the hull, but well towards the back, and close to the contact points of the wheels, showing that the manikin is close to tipping backwards. This analysis can thus be used to cover the various balancing conditions both of the wheelchair and that of the manikin when sitting in it. The changing of this balancing point can thus be chosen to increase the stability (or instability) to meet the users requirement.

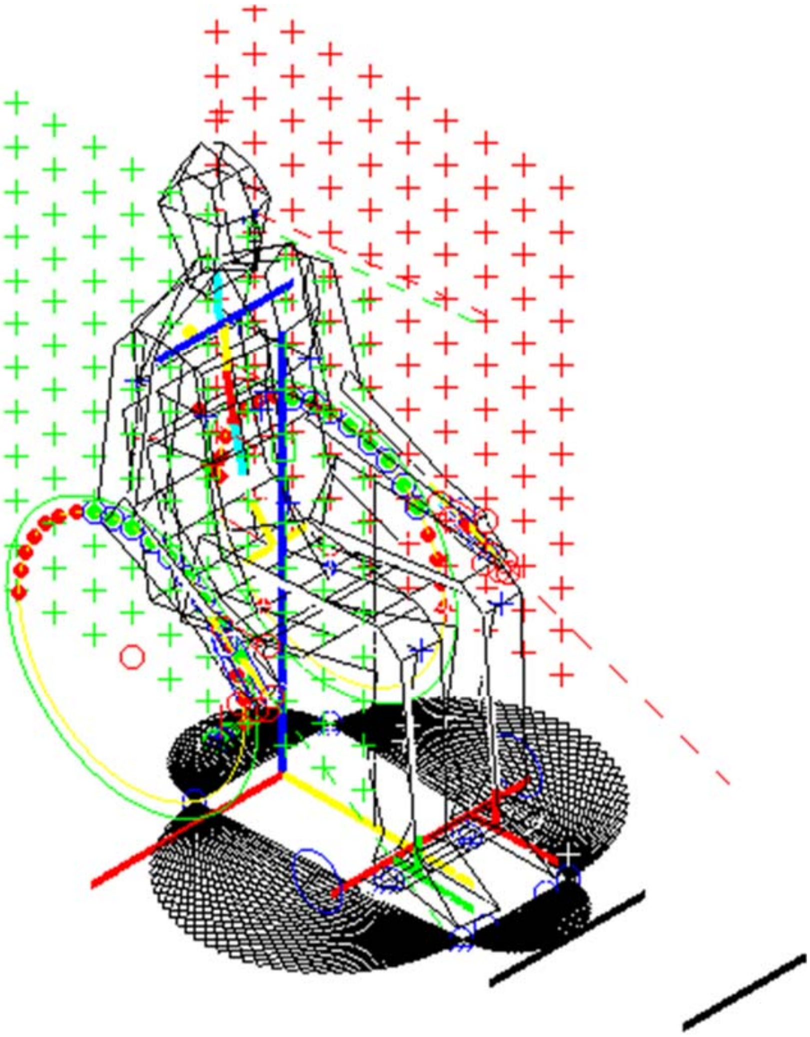

Figure 9. Manikin shown with hull constructed around all contact points

5. Conclusions

The spinning hull approach, when applied to the manikin studies, has provided a quicker and easier method of creating a convex hull than that of the standard methods. It has been found to be readily adapted to create any form of hull, and to be able to quickly determine whether the centre of gravity of the manikin is either inside, or outside, of the hull, in order to determine balance and posture. Rules for the balancing conditions can then be incorporated within the constraint modeller to allow automated searches for balance postures to be determined.

Acknowledgement

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