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BALLET BALANCE STRATEGIES

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Abstract

Animating physically realistic human characters is challenging, since human observers are highly tuned to recognize human cues such as emotion and gender from motion patterns. The main contribution of this paper is a new model firmly based on biomechanics. The model has been developed to animate balance and basic movements of a ballet dancers. It is supported by computer simulated experiments and is showing good agreement with biomechanical measurements of real-life dancers.

KE: Pertective, what impact does the work have?

Keywords: Biomechanics, Balance Strategy, Weight shift strategy, Control Mechanism.

Nomenclature

The following symbols are used in this paper:

- \( \tau \) Joint torque
- \( \theta, \Delta \theta \) Joint angle and angular update
- \( k_s, k_d \) Spring constants
- \( \vec{r}_i \) Position of body part \( i \)
- \( \vec{r}_{cm}, \vec{r}_{cp} \) Position of center of mass and pressure
- \( m_i, M \) Mass of body part \( i \) and total mass
- \( p_j \) Contact point
- \( n_j \) Normal force at \( p_j \)
- \( f_j \) Contact force at \( p_j \)

Introduction

A long term goal of computer graphics is to increase realism and believability into computer generated animations and pictures [1, 31, 18, 5, 37, 4]. With improved rendering techniques, the lack of physical realism and believability is becoming increasingly obvious and annoying to the common observer, and one accompanying long term goal in animation is to increase physical realism by using physics to model plausible behavior and movement of computer models. This known as physics-based animation.

This paper studies biomechanical and ballet inspired balance and weight shifting strategies and is based on original work in [35]. Ballet is a balance art and is a prime focus for learning about human balance and weight shifting strategies. We will describe how to make a dynamic animation from the first of the basic positions in Figure 1 to obtain a quiet standing on one toe. To achieve the goal the articulated figure moves through the four sub-goals shown in Figure 2: Balancing on two legs, weight shift to the supporting leg, balancing on one leg, and balancing on the toe of one leg. The new model is firmly based on biomechanics and is supported by computer simulated experiments showing good agreement with biomechanical measurements of real-life dancers.
Survey of past work

The study of balance has been performed in at least three separate areas of research: Biomechanics, Robotics, and Animation. We will in the following highlight some research from these areas.

Biomechanics and the study of ballet: Ballet is an art-form, where balance plays a central role. Classical ballet techniques are thoroughly described in the literature, see e.g. [17, 43]. Biomechanical studies of ballet has mainly been studied through injury cases, e.g. [13]. In The studying of human balance there is two theories: Either we balance by controlling the center of mass directly or indirectly by controlling the center of pressure [28]. Empirical investigations have shown that the velocity of center of mass plays a role in balancing [44]. Empirical studies on real humans have been performed on balancing of humans versus the position of the center of mass [34] KE: Balancing humans versus center-of-pressure strategy, don’t you mean center-of-mass versus center-of-pressure?. Weight shifts have been measured using a force-platform [32, 33]. Finally, a thorough measurement of the properties of mass and inertia of human body parts may be found in [10].

Robotics: Early work on balancing robots may be found in [41]. Weight shift strategies for walking are often performed through dynamic walking machines, where there is more or less degree of control involved in the walking cycle [29, 24, 40]. Recently, a number of spectacular and stable humanoid robots have been produced starting with the Honda robot [22]. Especially in relation to our work, the center of pressure has recently been introduced as a stable control mechanism for balancing robots [21, 20].

Animation: A very early mentioning of simulated human motion is given in [2], and early implementations may be found in [16, 30]. The implementation of dancing models is only scarcely discussed in the literature, however one exception is [8]. A major inspiration for our work has been [26, 46], where center of mass is used to control the balance and motion of a humanoid model of varying complexity. Alternative to center of mass strategies are inverse kinematics e.g. [27], energy models e.g. [7], and learning approaches e.g. [11].

The Biomechanics of Quiet Standing

A human in quiet standing may be modeled by an articulated figure [26, 46] consisting of a set of joints and a set of links representing body parts. The set of possible joints consist of revolute (1 Degree of Freedom (DOF)), universal (2 DOF), and ball-and-socket (3 DOF) joints. In this work, we have used Wooten’s model [46], which contains 28 DOFs, and uses real measurements of the mass, \( m_i \), center of mass, \( \vec{r}_i \), and moments of inertia of all the body parts [10]. The ankle and hip joints is of particular importance for this paper, and they are modeled by an universal joint and a ball-and-socket joint respectively.

Traditionally in biomechanics and anatomy motion orientation is described in three planes: The Sagittal (\( x \)-axis), the Transverse (\( y \)-axis) and the Frontal (\( z \)-axis) plane. These planes are illustrated in Figure 3. Measurements of angles and positions are traditionally also performed in these planes [32] by projection onto the respective planes and axes. Typical projections are: The position of the center of mass, the position of the center of pressure, angle of joints, and the direction of gravity. To work with the projec-
In the rest of this article, it will be assumed that the model is placed on a planar floor, and the contact between the floor and the feet is represented by a set of coplanar contact points, \( \vec{p}_j \). The support polygon is defined as the 2D convex hull of all the contact points. The center of mass is of the human model is defined as

\[
\vec{r}_{cm} = \frac{1}{M} \sum_{i}^{N} m_i \vec{r}_i,
\]

where \( M = \sum_{i}^{N} m_i \) is the total mass, \( N \) is the number of body parts in the model, \( m_i \) is the individual weights of the body parts, and \( r_i \) are their locations.

Note that center of mass is not fixed w.r.t. any location of the body during motion of the individual body parts. The center of pressure is defined as

\[
\vec{r}_{cp} = \frac{1}{||\vec{n}||} \sum_{j}^{K} ||\vec{n}_j|| \vec{p}_j,
\]

(4)

where \( \vec{n} = \sum_{j}^{K} \vec{n}_j \) is the total normal force acting on the human model, \( \vec{n}_j \) is the normal force applied to the human model at the \( j \)’th contact point \( \vec{p}_j \), and \( K \) is the number of contact points.

For simplicity, a spring model for the floor contact forces is used, where the contact force of the \( j \)’th contact is

\[
\vec{f}_j = k^\text{contact}_s \left( \vec{p}_j - \vec{\hat{p}}_j \right) - k^\text{contact}_d \vec{\dot{p}}_j.
\]

(5)

In the equation, \( \vec{p}_j^{\text{initial}} \) is the initial point of contact, \( \vec{\hat{p}}_j \) is the current contact point, \( \vec{\dot{p}}_j \) is the velocity of the current contact point, and \( k^\text{contact}_s \) and \( k^\text{contact}_d \) are spring and damping constants. The vector, \( \vec{n}_j \), is calculated as the projection of \( \vec{f}_j \) onto the contact normal of the floor, and the tangential part is a simple model of frictional force.

Contact forces can only be repulsive, and attractive contact forces, \( f_j \), are therefore set to zero. Slipping is obtained by setting \( \vec{p}_j^{\text{initial}} \) equal to \( \vec{\hat{p}}_j \), when the magnitude of the tangential force component exceeds a multiple of the magnitude of the normal force component. \( ||\vec{f}_{\text{friction}}|| > \mu ||\vec{n}|| \).

The line of gravity is defined as the line going from the center of mass to the ground in the direction of the gravitational field. The point of intersection between the line of gravity and the floor is referred to as the projection of the center of mass. These concepts are illustrated in Figure 4.

Balance is defined as an objects ability to maintain quiet standing, where quiet standing is the state, where the projection of the center of mass is kept within the support polygon [23, 26, 46]. The implication is that the greater support polygon, the lower center of mass, the more stable the balance and vice versa. The human body has a highly placed center of mass over a rather small support polygon, and as such the human body behaves as an inverted pendulum. This will be further developed later.

In the remainder of this paper, control strategies for maintaining quiet standing and moving an articulated figure from one pose of quiet standing to another will be discussed.
Balance Strategies: Mass Center versus Pressure Center

In the following, two strategies for balance inspired by Biomechanics will be compared: The center of mass strategy and the center of pressure strategy. The analysis are done on an articulated figure in 3D based on [46] standing with parallel feet. The balance is controlled by the ankle [44].

The center of mass strategy is the traditional balance strategy for dynamic animation, where the angular change is controlled as a function of the projection of the center of mass onto the support plane [26, 46]:

\[ \Delta \theta = k_{cm} \left( r_{cm}^{\text{current}} - r_{cm}^{\text{target}} \right) - k_{d}^{cm} \nu_{cm}, \tag{6} \]

where \( \Delta \theta \) is the angular change of the ankle in the Sagittal plane, \( r_{cm}^{\text{current}} \) and \( r_{cm}^{\text{target}} \) are the projections of the current and target positions of the center of mass onto the anterior axis, and \( k_{cm} \) and \( k_{d}^{cm} \) are control parameters.

In the center of pressure strategy, the model uses the center of pressure to control the center of mass. The goal of this strategy is to calculate a desired position of the center of pressure, and use this for controlling the muscles.

\[ \Delta r_{cp} = k_{cp}^{cm} \left( r_{cp}^{\text{current}} - r_{cp}^{\text{target}} \right) - k_{d}^{cp} \nu_{cp}, \tag{7} \]

\[ r_{cp}^{\text{target}} = \Delta r_{cp} + r_{cm}. \tag{8} \]

\[ \Delta \theta = k_{cp}^{cp} \left( r_{cp}^{\text{current}} - r_{cp}^{\text{target}} \right) - k_{d}^{cp} \nu_{cp}. \tag{9} \]

where \( \Delta r_{cp} \) is the positional change of the projection of the center of pressure onto the anterior axis, and \( r_{cp}^{\text{current}} \) and \( r_{cp}^{\text{target}} \) are the projections of the current and target positions of the center of projection onto the anterior axis, and \( k_{cp} \) and \( k_{d}^{cp} \) are control parameters.

The center of pressure theory can be understood by looking at the human balance like the balance of an inverted pendulum. The center of mass is the top and on the floor is the center of pressure. When the positions are right above each other, it's a perfect balance. In order to change the balance to a new desired position. The center of mass can start an acceleration towards the new point by moving the center of pressure in the opposite direction. The same happens if you balance a match on your finger.

Figure 5 shows the resulting dynamics of the projected center of mass and the center of pressure on the anterior axis. The movement of the projection of the center of mass on the articulated figure start in a position on the heels to the desired position on the center of the feet (the center of the support area). The articulated figure manages to balance using both strategies, but the center of pressure strategy requires only approximately 1.5 sec. while the center of mass strategy requires almost 10 sec. to get a balance in the desired position. In addition, the center of pressure strategy also has the smallest amplitude of the oscillations of the center of pressure, which means that it has the best control over the contact with the ground. The articulated figure is also balancing in frontal plane, but in this plane the projection of the center of mass starts in the desired position in the center. We obtained similar results for the same tests on another model [35] than Wooten’s [46].

Dynamics of a Ballet Dancer

Quiet standing on the toe of one leg is central in all ballet training. This is demanding, since the dancer has to balance on a very small support polygon while at the same time looking at ease. We have developed strategies for obtaining a balance on the left leg with the right foot by the left knee as illustrated in Figure 2. The pose is used, when dancers turn in a pirouette, and it is perhaps the most basic of all balances in ballet training. Both in quiet balance and in...
Figure 5: Comparison of the dynamics of the ankle for the two strategies: (a) Center of mass strategy and (b) Center of pressure strategy. $r_{cm}$ is the center of mass and $r_{cp}$ is the center of pressure. Motion is restricted to the Sagittal plane.

most of the basic ballet exercises, the legs are strictly separated into the working leg (doing the exercise) and the supporting leg. Shifting the weight between the legs is basic, and it should preferably be done without drawing the attention of the audience.

Weight Shifting Strategies

The weight shifting strategy described in the following was inspired by the analysis of real dancers presented in the literature [32]. They showed that angle changes in the hips and ankles are nearly identical during a weight shift, and that the center of pressure starts moving towards the working leg and end up being on the supporting leg. The last result is only explainable from the center of pressure balance strategy.

To shift the weight, we designated the left ankle to be the controlling joint using (9).

KE: This figure do not show anything about parallel legs, it shows spine rotation, do we need another figure? Ballet dancers compensate for the hip rotation by a counter rotation in the lumbar region of the lower back [17], and therefore a control function in the spine is required. Dancers control the body center by the stomach muscles. Experience has shown that these stomach muscles are extremely important for aesthetic motion of the articulated figure [35], thus a control function in the pelvis is used to inhibit rotation in the Sagittal plane. Both control functions are modeled using a spring law similar to (1).

The final weight shift of the articulated figure is shown in Figure 2. The resulting articulated figure agrees with measurements performed on real dancers [32] as follows: The measured angle changes are nearly identical during the weight shift, and the center of pressure starts to move towards the right foot and ends in a position on the left foot. The last result are showed in Figure 5 KE: I hope I got
the right reference here? On the dm-axis zero is
between the center of the legs KE: I rewritten this
sentence, did I get it right? the negative numbers
are the foot of the working leg and the positive are
foot of the supporting leg.

Movement to Quiet Standing on One Toe
The final movements to obtain a one-toed quiet
standing is achieved by lifting the non-supporting
leg, and shifting from a foot stand to a toe stand,
see Figure 2. It is not difficult to raise the leg, how-
ever the major challenge is to keep balance on a very
small support polygon.
Two strategies have been developed: A strategy for
raising the right leg, and a strategy for making a
weight shift to the toe. Similarly to the weight shift-
ing balance strategy, both are based on the center of
pressure strategy.

KE: Maybe to pictures illustration content of this
pharagraph? To raise the leg, the left ankle is kept
as the controlling joint, and the center of pressure
strategy is used to keep the balance on the center of
the left foot. To shift the weight to one toe, the center
of pressure strategy is used in two steps: Firstly, for
the controlling ankle joint, and secondly to control
the toe joint, when the ankle has been straightened.
When the supporting area KE: polygon is getting
smaller the human bodys small deviations from a
stiff pendulum makes it necessary to have a control
of the center of mass at the left hip joint to maintain
the balance.
Lifting the right leg to an aesthetically pleasing pose
is performed using a spring law. The spine and
pelvis are controlled as explained in the previous
section.
The analysis of the results shows a motion of the
center of pressure, when the right foot let go of the
floor contact. This is not entirely in agreement with
measurements on real dances. Otherwise the result
shows a stable line.

Discussion
This paper has shown how you can use results from
biomechanics for developing strategies for dynamic
animations of an articulated figure of a human. The
focus has been on balancing strategies. The compar-
ison of the two balance strategies: Center of mass
strategy, and the center of pressure strategy showed
far the best results for the last one which we have
not seen it used for dynamic animation before. We
showed that using the center of pressure strategy
makes it possible to develop strategies for a articu-
lated figure of a human to balance in a very com-
licated position. The center of pressure strategy is
useful in all dynamic animations of a balancing hu-
man. But if the projection of the center of mass is
outside the area of support KE: support polygon?,
it will not be possible to use this strategy alone to get
the articulated figure back in balance.
We found out that when the human body is not sim-
ply a stiff inverted pendulum it is necessary to use
another joint than just the ankle to control balance.
This happens when one leg is lifted from the ground
because there is movement in the upper body.
From a ballet point of view, controlling the center
of pressure is also a way of controlling the contact
of the feet with the ground. Ballet-dancers are very
much aware of the relation between their feet and
the ground, since it strongly influences their balance,
their stance, and the audience’s impression of the
dancer’s body.
Balance and weight shifting are the most basic tech-
niques in ballet. Future steps in our research will be
to develop strategies for exercises on one leg.

KE: Implications/perspective of this work?

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