The Visual Categorization of Humanoid Movement as Natural

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Abstract. We examined naturalness judgements of movements generated by different control strategies with the goal of producing natural looking movements on humanoid robots and virtual humans. We displayed motion clips on both a humanoid robot and a computer graphic character. Fourteen synthetic motion generation algorithms were developed based on human motor production theories. Human movement was also motion captured. Experimental results relate the actuator bandwidth, the level of computational complexity in motion generation, and the perceived naturalness of motion. In Experiment 1 it was found that for the humanoid robot, low ratings of naturalness were obtained for rapid movement. However, Experiment 2 indicated that this effect appeared to not be due to specific features of the motor production techniques but instead due to a movement artifact generated by the humanoid robot.

1 Introduction

The generation of natural appearing motion for humanoid figures is a significant and challenging problem in humanoid robotics and computer animation. We tackle this problem by drawing on the visual perception of human movement, motor production in humans, and through the simulation of motion. We have developed fourteen synthetic motion production algorithms based on human motor production and computational considerations, and have tested these psychovisually in two experiments, both displaying motions using a computer generated figure *and* recordings of a humanoid robot. We reveal that computationally expensive motion generation techniques such as torque change minimization did not yield an improved percept of naturalness relative to more easily computed hybrid kinematic/dynamic techniques.

In Section 2 we discuss visual perception of human movement and illustrate its relevance to motion generation. In Section 3 we discuss motion production, theories of human motor production, describe the implementation of fourteen synthetic motion algorithms, describe motion capture and explain how we produced a collection of motion clips for use as experimental stimuli. The experiments are described, along with results and conclusions in Section 4 and a summary is presented in Section 5.

2 Visual Perception of Human Movement

There is convergent evidence which indicates that human movement forms a special class of motion to human observers. Given the critical nature of detecting the movements of others and interpreting their intentions it is understandable that humans would exhibit specialized abilities in the processing of human movement. This critical eye for the movements of others raises the issue of how the movements of humanoid robots will be seen and interpreted. This is potentially a large area of study and in the present study we focus in the area of visual cognition and what is necessary for humanoid movements to appear natural. Specifically, we examine a set of movements displayed on a humanoid robot and a computer graphics (CG) character and try to determine what motion and movement generation properties are crucial for the movement to be seen as natural.

Although it is commonly accepted that perception of human movement is special there has been little direct research into what specific motion properties are crucial for it to be recognized as a natural movement. However, various spatial and temporal features have been identified to play a role in the recognition of movement style [1–3]. Moreover, there is evidence that when recognition of movement style is possible it is performed with high efficiency [4]. In the current study we examine various synthetic movements generated by biomimetic production criteria with the expectation that perceived naturalness of the movement will modulate with the movement production technique as well as the mode of presentation. From this result we hope to find which properties of movement are salient for it to be perceived as natural or unnatural.

3 Production of Humanoid Movements

In this section we introduce the relevant theories of motor production, discuss their implementation and then describe how this was used to obtain stimuli for the perceptual experiment.

3.1 Theories of Motor Production

There are a large number of theories regarding the way in which the brain plans and orchestrates physical movements of the body. Theories vary according to the space in which planning occurs (intrinsic body coordinates or extrinsic environment coordinates), whether planning is purely kinematic or dynamic, and to what the level the theory of motor production incorporates the physical interaction of the body with its environment through biomechanical and physiological principles.

A consideration of extrinsic kinematic trajectory planning lead to the minimum jerk hypothesis [5–7] according to which motions are planned as trajectories in the physical environment satisfying minimization of the third derivative. Snap minimization was also investigated [5] but a general property of extrinsic kinematic planning is that point-to-point motions yield straight paths inconsistent with some empirical findings which have detected a curvature in point-point reaching motions [8–10]. The minimum kinaesthetic jerk model [11] circumvents this complaint by modelling the instantaneous stretch and limb's centres of mass yielding dynamically planned motion with minimal internal and external jerk. Alternatively, the minimum jerk virtual trajectory model [12] proposes that motion is planned using a minimum jerk trajectory but that this virtual trajectory acts as a guide for the actual limbs in the form of a spring-damper system between actual and target joint angles. Other researchers have attempted to explain the curvature of hand trajectories, proposing that motion is planned in intrinsic kinematic space according to straight paths in joint-angle space [13], or that motion is planned as a straight path in perceptually distorted visual space [14]. While animators have used the intrinsic dynamic method of minimum torque [15], it has been proposed that motions are indeed planned according to the minimization of torque change throughout motion [9]. Higher level models have extended this concept by proposing that the motion is planned according to the minimization of muscle tension change [16] or neural activation change. It has also been proposed that planning occurs as an optimization at the control signal level with a signal noise component proportional to the activation level and that the constraint is minimum end-point positioning error [17]. Finally, a class of theories based on the equilibrium point hypothesis [18] suppose that the body is controlled using equilibrium positions at which the forces generated by the muscles supporting a given joint are in balance while the actual muscle force results from a lower level of control based on these equilibrium parameters [19–21].

3.2 Implementation of Motor Production Strategies

We implemented 14 motor production algorithms. These included trajectories planned kinematically in Cartesian world space and joint angle space, dynamically simulated virtual trajectories, dynamics based optimization and hybrid kinematic/dynamic methods. The models were either based on or inspired by existing motor production theories, and were intended to generate motions in the form of joint angle trajectories given specific Cartesian hand-point targets and a fixed duration for the motion. We based our algorithms on a 30 DOF humanoid corresponding to a robot called DB [22]. A sequence of more than two target points is unconstrained regarding the passage time of any internal target points, but the target points may also be cyclic in which case the passage times of all but the first target (which is also the last target) are unconstrained.

Four models, minimum velocity (MV), acceleration (MA), jerk (MJ) and snap (MS) were based on extrinsic kinematic trajectory planning in Cartesian space. The 3D space-line trajectory of the hand was calculated using a three dimensional piecewise polynomial spline. The coefficients were calculated using a general derivative minimization strategy of arbitrary dimensionality [23]. The hand coordinates were then used to derive postures using the extended Jacobian inverse kinematics method [24]. Four models, minimum angular velocity (MAV), angular acceleration (MAA), angular jerk (MAJ) and angular snap (MAS) were based on intrinsic kinematic trajectory planning in joint angle space. The joint angles were represented by 30 dimension piecewise polynomial splines. The coefficients were calculated using the same algorithm as above. A minimum jerk virtual trajectory model (MJVT) was implemented using the MAJ trajectory as a virtual trajectory guiding a dynamic simulation of a 30 DOF humanoid using spring-dampers acting at each joint. One model was based on the equilibrium point hypothesis (EPH), and was implemented by calculating target postures satisfying each hand positioning target, and then calculating lambda parameters for each joint by inverting the exponential lambda force equation. Postures throughout the motion were then generated by dynamically simulating the motion, and calculating joint forces using the exponential force equation with lambda parameters linearly interpolated between the postures. Two models based on dynamic optimization, minimum torque (MT) and minimum torque change (MTC) were implemented using a time consuming gradient descent algorithm. A minimum jerk trajectory was used as a starting point for the optimization since minimum jerk is expected to approximate minimum torque change. Finally, two algorithms were designed with both optimal dynamics and computational efficiency in mind, the minimum torque postures (MTP) and minimum torque postures virtual trajectory (MTPVT). The MTP model calculated postures satisfying each hand positioning target with a minimal torque requirement to maintain the posture statically and minimum torque change between successive postures. A minimum angular jerk trajectory through these postures yielded the final motion. The MTPVT algorithm extended MTP by using the MTP motion as a virtual trajectory guiding a dynamically simulated humanoid using spring-dampers and each joint. Table 1 summarizes the synthetic motion models. A more detailed description of the models and their implementation was presented previously[23].

3.3 Human Motion Capture

In addition to the implementing synthetic motion production models, genuine human motion data was also recorded. The motion of a human subject was captured using three Optotrak camera arrays and a total of 22 strobing infrared markers distributed over the upper half of the body. The subject was instructed not to move their feet. Motions were specified using physical reaching targets and obstacles. The subject was instructed to perform motions slowly or quickly and each motion was repeated five times to ensure good quality capture data was obtained. The marker locations were logged by the Optotrak system, and the position of the markers on the body was recorded in a fixed posture with the arms by the sides. It was then possible to locate the markers on a synthetic humanoid of similar kinematic dimensions, and derive joint angles from marker positions using a least-squares Gaussian optimization algorithm [25].

3.4 Generation of Movement Stimuli

Animation clips were generated using the 14 synthetic models and the motion captured human movements (a total of 15 motion models). 7 different motions were performed yielding a total of 105 clips. The 7 motion specifications were designed to represent fast and slow, curved and straight, point-point and cyclic hand trajectories. Motions 1-3 were simple point-point movements performed in 4.2s, 0.3s and 0.3s respectively. Motions 4-6 were via-point (point-point but passing through an intermediate point) performed in 4.4s, 0.5s and 0.6s respectively. Motion 7 was cyclic, consisting of four target points in a circular arrangement performed in 4.8s repeated twice and thus lasting 9.6s. For all 6 non-cyclic motions a brief period was included at the start and end of each clip so that the onset and termination of motion could be perceived. The clip durations for the motions were thus 4.5s, 1.5s, 1.5s, 5s, 1.5s, 1.5s and 9.6s.

Figure 1 summarises the motions used for testing. The motions were prepared offline and stored as posture (complete joint-angle) samples taken at 70Hz. Clips showing a computer generated synthetic humanoid were generated by converting the motion logs to BVH format and importing the motions into MetaCreation's Poser software which was used to render AVI files. Clips showing a humanoid robot performing the motions were generated by having the robot perform the

Table 1. Categorization of synthetic motion models. Categories include intrinsic/extrinsic planning, sophistication of the planning process and whether forward dynamic simulation is involved

Name	Model	Planning space	Planning level	FD
MV	Min. velocity	Extrinsic	Kinematic	No
MA	Min. acceleration	Extrinsic	Kinematic	No
MJ	Min. jerk	Extrinsic	Kinematic	No
MS	Min. snap	Extrinsic	Kinematic	No
MAV	Min. angular velocity	Intrinsic	Kinematic	No
MAA	Min. angular acceleration	Intrinsic	Kinematic	No
MAJ	Min. angular jerk	Intrinsic	Kinematic	No
MAS	Min. angular snap	Intrinsic	Kinematic	No
MJVT	Min. jerk virtual trajectory	Intrinsic	Kinematic	Yes
EPH	Equilibrium point hypothesis	Intrinsic	Dynamic	Yes
MT	Min. torque	Intrinsic	Dynamic	No
MTC	Min. torque change	Intrinsic	Dynamic	No
MTP	Min. torque postures	Intrinsic	Dynamic	No
MTPVT	MTP virtual trajectory	Intrinsic	Dynamic	Yes

motions and recording them using Digital Video. The recordings were subsequently cropped to the appropriate durations and stored as AVI files using Adobe Premiere.

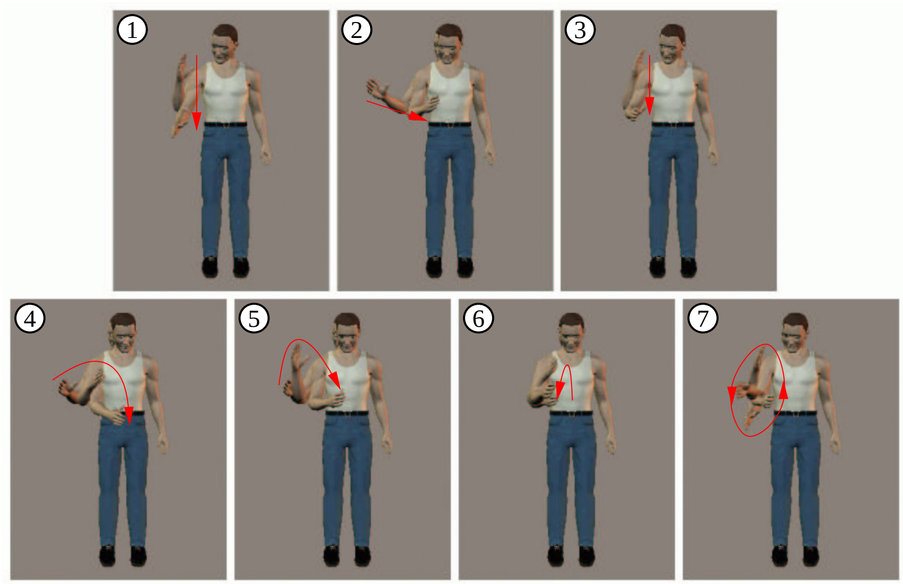

Fig. 1. Motions used for psychovisual testing

4 Experiments

Two experiments were performed that examined naturalness ratings of a set of movements that included motions generated by 14 different motor control strategies as well as motion captured human movement. In Experiment 1 these movements were played back on both the humanoid robot and a computer graphics (CG) character. Results indicated systematic differences in ratings of naturalness for the movements played back on the humanoid robot and Experiment 2 examined the nature of these obtained differences.

4.1 Experiment 1 - Naturalness Judgements of Humanoid and CG Movements

Experiment 1 explored how successful the various movement generation techniques were at providing the impression of a natural human movement. Observers viewed individual movements and judged how natural they appeared. It was expected that the naturalness judgements would provide a basic view of whether or not a particular technique was successful in generating movements which appeared natural.

Design and Methods. The effect of three variables on the perception of natural movement were examined. These were a) movement production technique with 15 levels corresponding to the 14 generation techniques plus motion capture; b) movement, with 7 levels corresponding to the different movements described in Section 3; and c) body, with 2 levels corresponding to whether the movement was played back on the humanoid or CG character. The variable of body was run as a between-subjects variable with half the observers making judgements from the humanoid and the other half from the CG character.

A total of 20 observers volunteered to participate in the study and were randomly assigned to either the humanoid or CG movement presentation. Each participant was instructed to view the movement shown as a motion clip on a computer monitor and at the completion of the clip to enter a rating from 1-10 of the naturalness of the movement. The scale was defined so that low ratings corresponded to unnatural movements and high ratings to very natural movements. Participants could repeat viewing of the clip until they were confident of their response.

Results. The results of Experiment 1 produced significant effects of the three experimental variables as well as interactions between the variables. These results can be viewed in Figures 2 which plots, for each of the 7 movements, the average naturalness ratings for the humanoid and the CG character for the 15 production techniques (error bars indicate the standard error of the mean). These results are replotted in Figure 3 to facilitate comparisons between the different movements. Overall, these results show that for any one particular movement, whether presented via humanoid or CG character, there was little systematic variation of naturalness ratings with production technique. However, exceptions to this include an apparent decrease in naturalness ratings for the EPH technique for most combinations of movement and production techniques and a decrease in naturalness ratings for movement 7 with the MAV and MV production techniques. Examination of Figures 2 suggests that for movements 2, 3, 5 and 6 there was a large difference between humanoid and CG character ratings of naturalness, while for movements 1, 4 and 7 there was not. This is also seen in Figure 3 for the humanoid where a gap is visible between the 3 movements with the highest ratings and the 4 movements with the lowest ratings. Since movements 1, 4 and 7 were slow movements and 2, 3, 5 and 6 were fast it would appear that this effect would somehow be related to the speed of the movement. This dependence of naturalness rating on movement was not visible for the CG character which displayed no strong effect of either movement or production technique on naturalness ratings.

To further explore these effects evident in the figures an ANOVA was performed that incorporated the two factors of production technique and movement type as within-subjects variables and presentation type as a between-

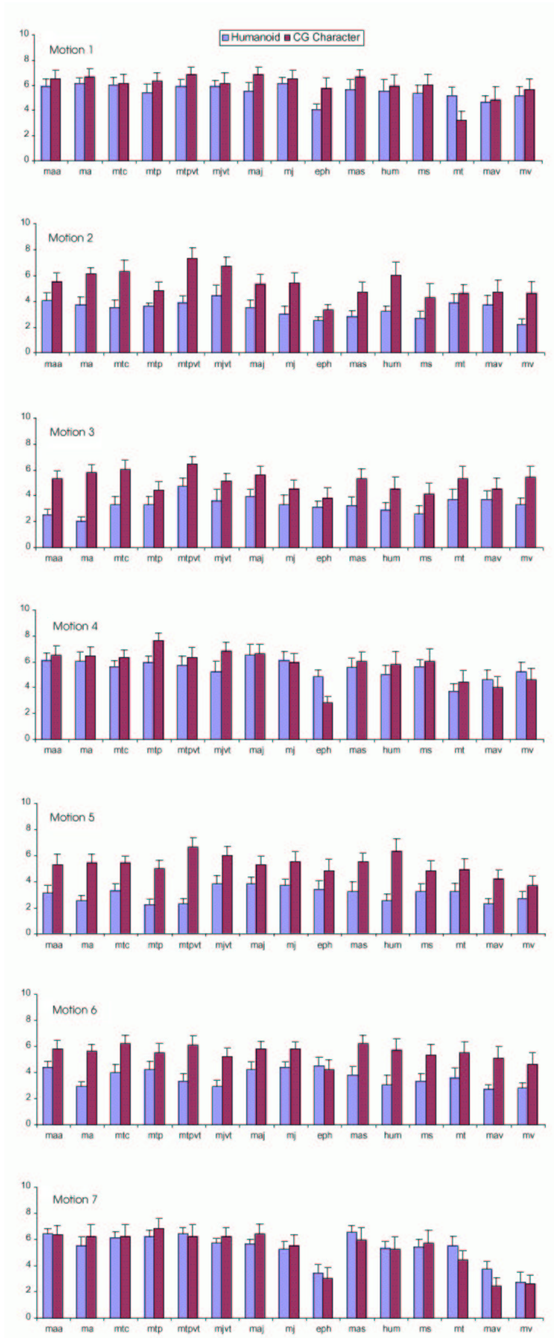

Fig. 2. Mean and standard error of the mean of naturalness ratings for each motion generation model and each movement

subjects variable. Results showed significant main effects of production technique, $F(14, 252) = 7.6, p < 0.001$, movement, $F(6, 108) = 9.4, p < 0.001$, and body, $F(1, 18) = 5.7, p < 0.05$. Interactions were found between body and movement, $F(6, 108) = 4.4, p < 0.001$, as well as between production technique and movement $F(84, 1512) = 3.0, p < 0.001$. This analysis is consistent with the basic interpretation of the figures presented above.

Since speed appeared to have a large effect on naturalness judgements for the humanoid robot we will use the results in Figure 3b with the CG character to examine the relation between naturalness judgements and computational considerations of the motor production technique. Overall techniques MV, MAV are poor, probably because the velocity is discontinuous when the hand path which is a straight or nearly straight line changes direction. Techniques MA, MAV, MJ, MAJ, MS & MAS all appear good, indicating (by comparison with MV and MAV) that a continuous velocity profile is necessary for natural motion but that a continuous acceleration profile (in MJ, MAJ, MS, MAS but not MA, MAA) is not so significant -at least with the presentation mode used in the current experiment. Techniques MTP and MTPVT are good, particularly by comparison to MT and MTC indicating that the full motion dynamic optimization of MT and MTC can be reduced to a smooth interpolation of statically MT postures interpolated with MTC. Technique MTC is fairly good, but our results indicate that full MTC optimization is not necessary to generate natural appearing motion (at this resolution) which is valuable information since the computation is extremely expensive. Technique MT yields varied results, most likely because MT optimizations over slow movements can produce unexpected types of motion (*i.e.* pendulous swing for slow point-point movements).

Technique EPH yielded bad motion most likely because the implementation was based on linear interpolation of the lambda parameters with an exponential force generation equation and did not include a velocity damping term so that motions tended to be unstable. It is difficult however, to draw conclusions about the general EPH model because there are many different formulations but none provide a complete description of the generation of motion from a computational perspective. While the incorporation of velocity damping improves the stability of generated motion, it was found both empirically and analytically that the resultant divergence between MJVT and EPH was negligible. The selection of an EPH implementation without velocity damping was motivated by a desire to obtain a contrast in the perceived quality of motions.

Discussion. One notable result of Experiment 1 was the effect of movement speed on the judged naturalness of humanoid movements. This is a somewhat surprising result since there is no reason why a fast movement should necessarily be judged as less natural when displayed on a humanoid. Thus, it would seem likely that the naturalness judgements were being modulated by some artifact of the humanoid moving quickly. Informal examination of the humanoid movements revealed that for the fast movements there was a tendency for the humanoid to slightly wind-up its shoulders at the beginning of a movement and to

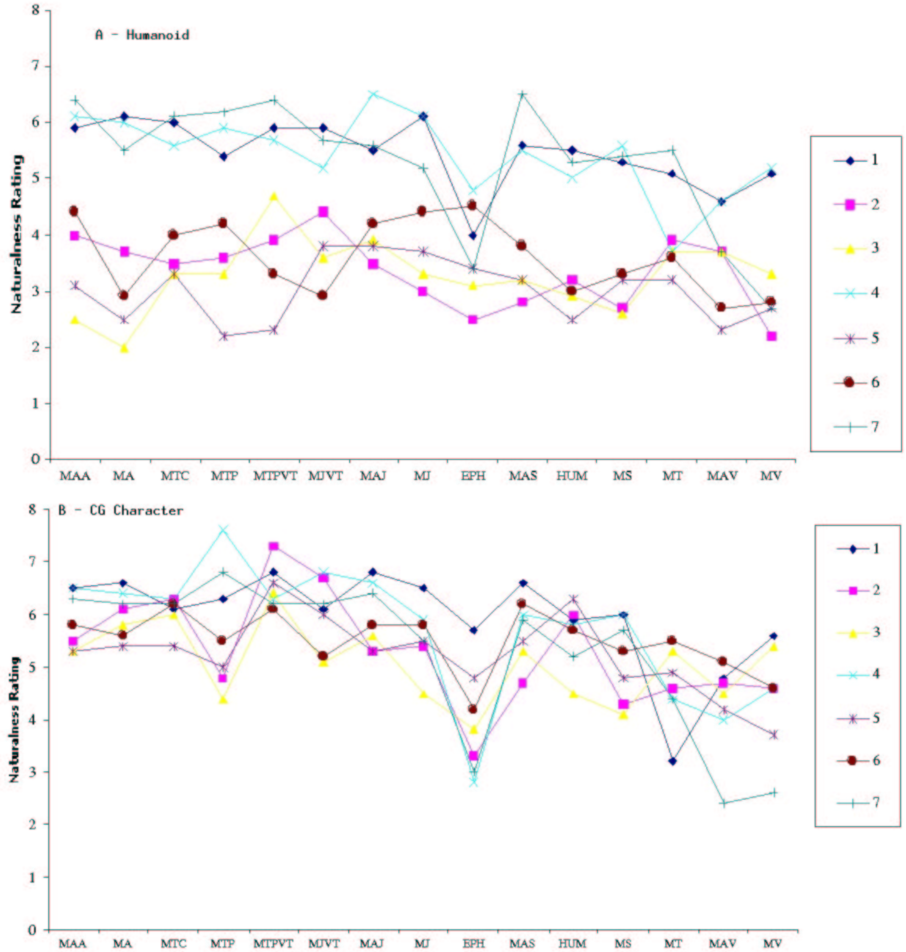

Fig. 3. Results of naturalness ratings for the humanoid (A) and computer graphics character (B) are shown. Results are shown for each of the 7 movements at each of the 15 different motion production techniques

shake at the termination of the movement. This shake was characterized by the entire torso and head appearing as a rigid body shaking in reaction to the forces generated by the deceleration of the hand. In order to explore this hypothesis more closely we performed a second experiment where the ends of the motion clips were edited to eliminate as much as possible any movement but that of the hand moving between positions. Before proceeding to describe Experiment 2 we discuss another result from Experiment 1, that naturalness ratings seemed broadly unaffected by movement production technique. While differences were noted, they are less than what would be expected if naturalness ratings gave a sensitive probe into the perception of human movement. Evidence for this comes from the fact that the movement generation technique did occasionally generate quite unusual solutions that did not stand out by human judgements to appear unnatural. For example, movement 4 generated by MT began with several pendulous swings of the entire arm to bring it from one point to the other and though its ratings were generally lower than average they certainly do not reflect the unnaturalness of this motion in obtaining a point-to-point arm movement. In this respect, what naturalness judgements appear to lack is any insight into the goal of the movement. While this lack of insight into the goal of a movement is entirely understandable within the context of the present experiment it would seem reasonable to conjecture that judgements of naturalness provide only a general sense of whether a movement is a possible human movement, rather than a sensitive measure of the detailed properties of the movement.

4.2 Experiment 2 - Effect of Speed on the Humanoid Robot Movements

Experiment 1 indicated that the faster movements, when displayed on the humanoid, appeared less natural than slow movements and it was hypothesized that the cause of this difference was due to movement artifact. Experiment 2 examined this hypothesis by taking the original video clips and editing them so that they began when the hand started in motion and finished on the first frame that the hand reached the endpoint. This substantially reduced or eliminated any extra motion at the ends of the movement. These original and edited video clips were shown to participants and their naturalness judgements obtained.

Design and Methods. The variables of movement speed (fast, slow) and movie editing (original, edited) were examined in Experiment 2. The original 105 movies (7 movements $\times$ 15 production techniques) were edited to create a new set of 105 movements. This editing was done by hand and reduced or eliminated any additional motion at the end of the movement. We attempted to crop all the movements at the first minima of velocity at the end of movement. This meant that the clips were no longer of uniform duration, but the variability was only a few hundred milliseconds. Five participants volunteered to view the 210 movies (105 edited and 105 original) and judge the naturalness of the humanoid motion. The results were recoded so that the circular movement (movement 7) was eliminated from consideration and responses to movements 1 and 4 were averaged together to obtain values for slow movements and movements 2, 3, 5 and 6 were averaged together to obtain values for fast movements. This resulted in a 2×2 design examining the effects of movement speed and whether or not the movie had been edited.

Results. The results of Experiment 2 can be seen in Figure 4, which displays the mean of the four different conditions with error bars that indicate 95% confidence intervals. It can be seen that for the original video clips there is a significant effect of whether the movements were fast or slow but that for the edited video clips there was no significant effect of the speed of the movement.

Figure 4. The results of Experiment 2 comparing the perception of naturalness for the original movements and their edited versions for both the fast and slow movements. Error bars indicate corrected 95% confidence intervals. As can be seen the effect of movement speed is evident for the original movements but is diminished and does not reach statistical significance for the edited movies.

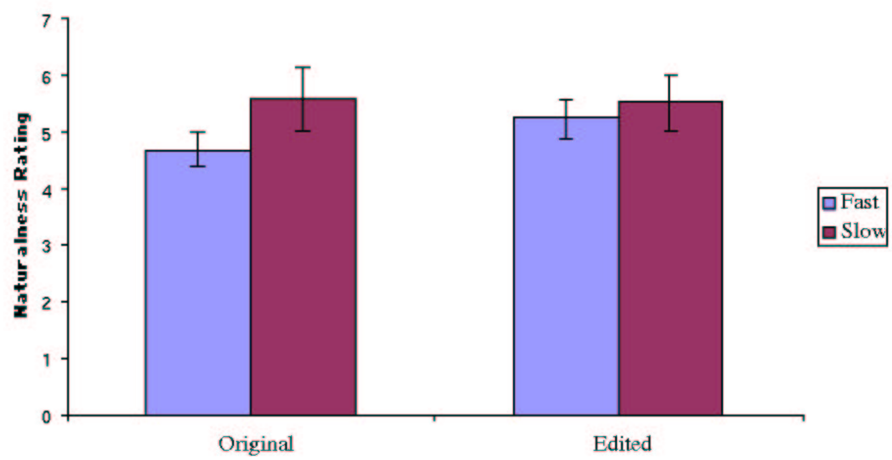

Fig. 4. The results of Experiment 2 comparing the perception of naturalness for the original movements and their edited versions for both the fast and slow movements. Error bars indicate corrected 95% confidence intervals. As can be seen the effect of movement speed is evident for the original movements but is diminished and does not reach statistical significance for the edited movies

Discussion. The results of Experiment 2 were consistent with the hypothesis that the lower naturalness ratings for the fast movements on the humanoid robot were not due to the hand motion per se but rather movement artifact resulting from the rapid hand movement. At its worst this artifact is manifest as a shake that makes the humanoid robot appear as if the torso, head and opposite arm are a rigid structure that is passively reacting to the rapid deceleration of the moving arm. As such it appears distinctively mechanical and it would seem that the low naturalness ratings are influenced by this qualitative appearance of a motion style that is characteristically inanimate.

5 Summary and Conclusions

We designed and implemented 14 synthetic motion production algorithms based on a study of human motor production research. Psychovisual experiments were performed using the synthetic models, and including motion captured human movement in order to assess the relative naturalness of the models.

The first experiment asked subjects to rate the naturalness of individual motion clips, and revealed some general conclusions appropriate to the resolution of display medium used (AVI files of a CG humanoid or video recorded robot). Continuous velocity profiles of the hand trajectory are significant features of natural movement but continuous acceleration profiles are not very important. Time consuming dynamic optimizations such as minimum torque and minimum torque change do not offer significant benefits over much simpler motion production algorithms.

However, it was also concluded that judgements of naturalness alone are not broadly informative because the goal of a given motion is probably significant to its perceived naturalness. The results obtained for the humanoid robot, and experiment 2 in particular, reveal that the results were influenced by mechanical artifacts of motion, *i.e.*, fast movements cause perceivable shakes at the termination of motion. The results comparing motion models could not therefore, be claimed for fast movements on the robot but do appear in the slow motions. The MJVT and MTPVT models for example, which incorporate dynamic smoothing do not appear better on the robot because the smoothing properties are only significant for fast motions.

Additionally, the dynamic smoothing incorporated by the virtual trajectory models (MJVT & MTPVT) is implicit in any motion performed by the robot which is necessarily subject to the robot's own spring-damped low level controller and the action of physical laws. All of the derivative minimisations (MV, MAV, MJ *etc.*) therefore act as virtual trajectories according to the gain parameters of the robot's low level control. Also, the other dynamically optimised models (MT, MTC & MTP) were synthesised for the robot's kinematic and dynamic characteristics but did not appear to capture the *loose* or *relaxed* qualities one might expect from dynamically optimal motions. Both of these issues are related to the actuator bandwidth (the low level controller operated at 420Hz) and the sampling rate of the trajectory files (70Hz). The notion of performing under stiff control, a trajectory that has been optimised for minimal torque or torque change may be flawed in the sense that it is necessary to perform motions with reduced torques in order to capture the appearance of relaxed motion. This is dependant on the acuity of human perception, and ideally, the appearance of relaxed motion could be achieved with comparatively stiff joint torques to avoid the inherent danger of instability or collision that arises as joints become looser. The threshold of actuator stiffness parameters versus the percept of natural and/or relaxed appearing motion is a topic for further research.

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