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Interpersonal Distance Modeling During Fighting Activities

Gilles Dietrich, Jonathan Bredin, and Yves Kerlirzin

The aim of this article is to elaborate a general framework for modeling dual opposition activities, or more generally, dual interaction. The main hypothesis is that opposition behavior can be measured directly from a global variable and that the relative distance between the two subjects can be this parameter. Moreover, this parameter should be considered as multidimensional parameter depending not only on the dynamics of the subjects but also on the "internal" parameters of the subjects, such as sociological and/or emotional states. Standard and simple mechanical formalization will be used to model this multifactorial distance. To illustrate such a general modeling methodology, this model was compared with actual data from an opposition activity like Japanese fencing (kendo). This model captures not only coupled coordination, but more generally interaction in two-subject activities.

Keywords: interpersonal interaction, modeling, interpersonal distance, motor coordination

Like any animals, humans observe certain distances in their relationships with their peers. These distances are fundamental for the construction of a space necessary for balance. In their relationships with others, humans as well as other animals build fields (distances) which are in constant development, depending on factors like the situation or the social status of the opponents. Hall (1966) proposed a classification of these distances: intimate, personal, social and public. The intimate distance is used for sexual acts and fighting. In these situations, the relationship between the subjects is characterized by physical contact. Personal distance, also proposed by Hediger (1961), represents the minimum distance acceptable to each individual in society and the space surrounding the individual, between 0.45 and 1.20 m.

The social distance (between 1.20 m and 3.60 m) is the distance observed by a subject and the members of his group. Finally, the public distance (beyond 3.60 m) is a space used by very important people (political, actors, etc) to guarantee security. In virtual environments, researchers (Bailenson, Beall, Blascovich, Weisbuch, & Raimmundo, 2001; Bailenson, Blascovich, Beall, & Loomis, 2003b; Krikorian, Lee, Chock, & Harms, 2000; Sommer, 2002; Bailenson et al., 2001; Bailenson,

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Blascovich, Beall, & Loomis, 2003a) have studied personal and interpersonal space (i.e., the personal distance proposed by Hall). They showed that interpersonal space is influenced by the presence of another person and depends on the location of the individual, the sex and the gaze.

This concept of interpersonal distance is also present in the animal world. For example, it is very difficult to approach wild animals without triggering an escape response. Hediger (1961) calls this spacing between individuals *the escape distance*. This distance depends on the animal's size. If the animal is very large, this distance (which must be maintained between itself and its enemy) is great. Conversely, if the animal is small, the distance is reduced. Hediger (1961) also identifies a critical and an attack distance. The critical distance is the narrow zone which separates the escape distance from the attack distance. Finally, when another animal enters the attack distance, it triggers aggressive behavior against the undesirable visitor. For predators, this is also the distance in which to catch prey. This distance is defined according to the abilities and characteristics of the animal. This interaction between biological entities has also been studied in wolves (Golani & Moran, 1983; Moran, Fentress, & Golani, 1981) and in badgers (Yaniv & Golani, 1987). These authors emphasized that these animals try to maintain geometrical values as the relative distance which separates the two animals or their relative orientation. They showed that this relationship is influenced by the social status of the animal (dominating *vs* dominated). In particular, Golani (1992) showed that the gradient of mobility (i.e., number of possible movements) depend on this social status. Dominating animals have a much greater gradient of mobility than dominated animals. Thus, social status acts like a constraint in this interindividual relationship, offering the dominating animal a larger sphere of activity while reducing that of the dominated animal.

In humans, the distance variations observed between individuals seem to depend on different factors, such as the cultural background, the temperament (dominant/dominated), the size, the psychological state and even the surrounding setting (Hall, Coats, & LeBeau, 2005). In this condition, the perception of space cannot be considered to be a static parameter but a dynamic variable related to action, environment and the relationship with others. This *dynamic distance* could be also observed in a case of interpersonal interactions or oppositions between two subjects. Recent studies have investigated interpersonal relationships in activities like fencing (Dietrich, Bredin, Hanneton, Megrot, & Kerlirzin, 2005), walking (Ducourant, Vieilledent, Kerlirzin, & Berthoz, 2005), tennis (Palut & Zanone, 2005) and basketball (Schmidt, O'Brien, & Sysko, 1999). One special case of interaction is called *coordination* and most of the literature deals with this aspect. Greatly inspired by studies on interlimb coordination movements between two individuals (Schmidt, Beek, Treffner, & Turvey, 1991; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Temprado & Laurent, 2004), these experiments assume that the interpersonal relationship is based on two nonlinear coupled oscillators. Research has shown that spontaneous patterns of coordination occur in such rhythmic movements, i.e., in-phase and out-of-phase mode (Haken, Kelso, & Bunz, 1985; Kelso, Holt, Rubin, & Kugler, 1981; Kelso, 1982, 1984; Schöner, Haken, & Kelso, 1986). These two preferred stable patterns (the in-phase pattern being more stable than the out-of-phase pattern) have been modeled by Haken et al. (1985). The sudden and completely involuntary switch from an in-phase pattern to an out-of-phase pattern occurs when oscillatory frequency, called the control parameter, increases beyond a critical cycling frequency. The nonlinear coupled oscillators model provides an interesting theoretical framework for investigating interlimb coordination or interpersonal interaction. However, a study by Ducourant et al. (2005) clearly shows that coordination requires that subjects follow instructions (e.g., to maintain the initial intersubject linear distance). Thus, the question arises of whether the modeling of an actual fighting situation elaborated on the basis of two nonlinear coupled oscillators could explain the interpersonal interaction and not only coordination induced by an experimental situation.

The aim of this study was to investigate the control mechanisms of this multifactorial distance in the case of an interaction or opposition task using a modeling and simulation methodology. This approach suggests that an a priori model could be proposed and experimental data should validate or invalidate such model. This a priori model summarizes our hypothesis, and its main advantage is that these hypotheses can be described in terms of equations. When two (or more) subjects interact, we hypothesize that an *interacting* distance is built up and controlled during an initial phase called the preparation phase, and is more or less maintained during an observation or coupling phase. The main contribution of our model is to consider that actual distance is depending not only on motor parameters but also on psychological and decisional factors as well. That means that an interaction model should include at least these three dimensions of control parameters.

In the real world, the coupling phase cannot be maintained for the long run. So, we need to add a last phase called the de-coupling phase. During this last phase, distance interaction will be broken. This distance is in fact an *instantaneous distance* depending on the subjects' displacements and actions but also on the emotional state and/or the sociological status of the subject as previously described. The spatial and temporal aspects of the interacting movements of the individuals are mutually related (Schmidt et al., 1999). This multifactor notion incorporates time and cadence in a single concept of metric distance. For convenience, we use the global term *distance* to represent all of these parameters. The model we propose should let us take into account the different times of the interaction, but more importantly, this modeling methodology should let us include not only kinematic or dynamic parameters but emotional and/or decisional components as driving parameters. In other words, this model should capture not only coupled coordination but more generally interaction between the activities of the two subjects.

The main problem with such a modeling procedure is that the system composed of two individuals could be qualified as a complex system. What do we mean by the term complexity? By this we mean a system that can be defined by multiple interactions of its components. For example, a gas composed of an *infinite* number of particles is considered a complex system if one wishes to measure or define the behavior of a single particle (Boltzmann, 1872). A complex system exhibits different fundamental attributes such as a high level of interaction, many independent degrees of freedom, nonlinear behavioral output and the capacity to spontaneously shift between different coordinated states. This complexity can also be observed in biological systems, even if the apparent number of elements is small or weak. Such a physical model of complexity could cover biological behavior. Yates (1979) underlined the opportunity to relate behavior in biological systems (like an interaction task between people) to physical principles. Theories of self-organization systems are an example of the application of physical science to the study of behavioral patterns (Prigogine & Stengers, 1979). This study adheres to the general philosophy that human complex behavior can be captured and summarized by physical principles. For instance, this global approach has been used to understand complex behavior like human rock climbing (Cordier, Dietrich, & Pailhous, 1996). In this article, the interaction between subject and environment was modeled using a simple harmonic oscillator and rock climbing was considered as a constraint of vertical locomotion. This general approach supposes that to illustrate the model's ability to capture interaction processes in an actual task, simulation results should be compared with actual data. In everyday life, human subjects must plan and generate their locomotor displacements according to physical and environmental constraints. However, the displacement or trajectory of another person may constitute this constraint according to which the subject must adapt his behavior. This is observed in physical activities or sports, and more particularly in team sports (e.g., rugby, basketball) and direct opposition sports (e.g., French boxing, kendo). Here, the correct intersubject distance is a key to scoring or winning. In fact, the subject must reach the opponent while avoiding being reached by him or her. The concept of distance takes on great importance particularly in fighting sports. Since the 12th century, this concept has been historically and philosophically developed by Japanese culture under the notion of *ma-aï*.

In kendo, the aim of the game is to touch without being touched. There is more than one strategy to reach this goal. Most often, the two fighters keep their weapons (bamboo sword) in contact and the distance between the two fighters is regulated not by the distance between the two weapons tips but by the point of contact. In our model, this point of contact was defined as the center of movement. Moreover, this contact could be analyzed as a way to exchange information between the two fighters during the coordination phase. These are the main reasons why Japanese fencing, called *kendo*, was chosen for this paper.

Models

Description of the Model

To describe the dynamics of interaction between two fighters, we propose a model which has to deal with three components: 1) the preparation phase in which the interaction distance is constructed and the next phase established 2) the observation phase, representing the critical distance between both combatants and during which coordination emerges and 3) the rupture phase in which this distance is broken to touch the opponent. This phase is characterized by chaotic behavior. Our system is composed of individuals, which means that we have to consider different levels of parameters: 1) task parameters like the size of the weapon (here called *shinai*), mass inertia and valid target 2) psychological parameters like decisional and emotional aspects and 3) biomechanical parameters such as subject mass and musculo-skeletal characteristics. This model was initially built independently of our experimental study. Only model parameters were optimized to fit experimental data. In this study we explicitly used basic mechanical equations to simulate complex human behavior. From a general point of view, this paper argues complex system either human or animal, could be explained using the same or adapted general framework like physical interaction.

In the preliminary model, the subjects were modeled by a particle system with each moving in a one-dimensional space (see Figure 1). This one physical dimension represents the curvilinear trajectory described by the subject's motion. In the results section, we will show that this approximation fits actual data well. We assume that the actual distance is fully defined by the position of the subjects along this axis. The origin of the frame of reference attached to this space is defined by the center of movement (C). Distance (r) can now be split into two parts x_1 and x_2.

The isolated particle system model was chosen because we considered only global subject displacement and center of mass trajectories. Particle kinematics will be defined by a set of differential equations. To investigate the three components of our system, we established three different sets of equations defining all interactions between particles.

Interaction Between Two Particles

Preparation Phase (or Attraction Phase). The first equation was introduced to capture the preparation phase. During this phase, two particles are located in a one-dimensional space separated by a great distance (depending on the task constraints, for example 3 m in kendo). The first interaction must be a distance interaction creating forces between two particles, effectively moving the two particles closer together. This simple and obvious interaction is called *central force*.

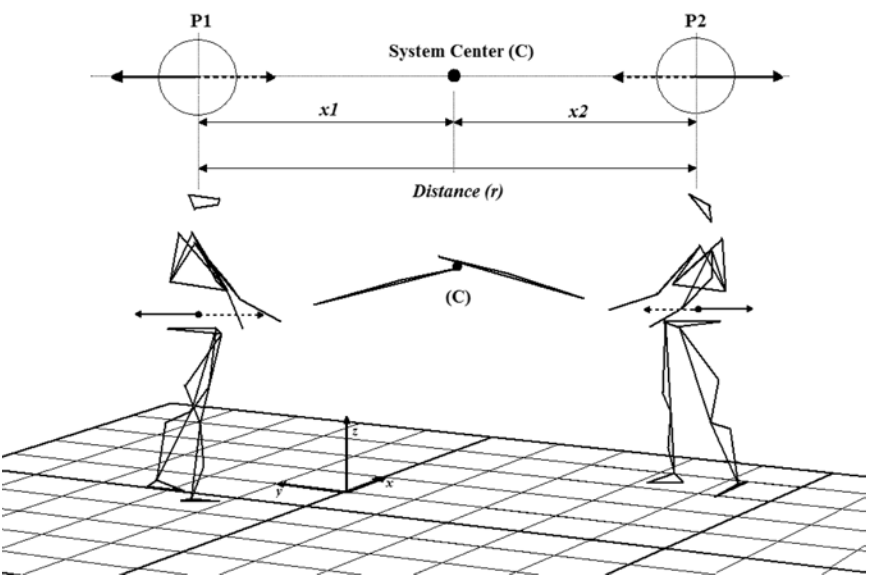

Figure 1 — Fighters representation and particle model. This figure shows a typical representation of two fighters (P1 and P2) recorded by the 3D kinematic system and its representation in a particle model. The principal distance (r) is the sum of ×1 (distance between Subject 1 and C, center of the two fighters) and ×2 (distance between Subject 2 and C). The arrows represent the interaction forces acting on each subject.

Let P1 represent the first particle and P2 represent the second particle with m_1 and m_2 being the respective masses. The interaction is represented by Equation 1:

$$K_G \cdot \frac{m_1 m_2}{r^2} \tag{1}$$

where r is the distance between the two particles and K_G is a gravitational constant defining the force of opposition. The main advantage of using such an equation is that it necessarily leads to the destruction of this two-particle system, and if m_1 and m_2 are very close, we could simplify this equation as:

$$K_G \cdot \frac{m^2}{r^2} \tag{1'}$$

A central force acting on particle P1 depends only on the distance of that particle from the origin (C):

$$F = F(r)\hat{r} \tag{1''}$$

where $\hat{r}$ indicates a unit vector in the same direction as r.

In any case, attraction forces depend only on distance, and the gravitational constant could be assumed to be a part of task constraints. For example, if the task is to attack within a definite time, this so-called constant could be transformed into a scalar value depending on time: $K_G\,(t)$. This variable could increase with time and in the same direction as the force of attraction. Figure 2 shows three constant values for K_G and one variable parameter (linear function of time) showing that these gravitational parameters could directly modify the dynamics and consequently the kinematics of global movement.

Coordination Phase. Fighting activities are not composed solely of attraction and destruction. Fighting exhibits an observation phase in which the distance between the subjects is more or less maintained. This phase is characterized by an emergence of coordination between the kinematics of the subjects. This emergence could be considered as the net result of opposite forces acting on each subject or particle. Equation (1) has already defined one type of force, but a second set of equations is needed to produce this phase. This second equation defines a linear mass spring pendulum:

$$K_S^1 . x_1 + K_V^1 . \frac{dx_1}{dt} + \frac{d^2 x_1}{dt^2} = 0 \quad \text{for particle 1} \tag{2a}$$

$$K_S^2 . x_2 + K_V^2 . \frac{dx_2}{dt} + \frac{d^2 x_2}{dt^2} = 0 \quad \text{for particle 2} \tag{2b}$$

where K_S^i is the global stiffness corresponding to the whole body stiffness for particle i and K_V^i represents the global viscosity of the whole body. These two parameters could easily be compared with impedance defined by, and related to, the intrinsic parameters of the subjects: x_1 and x_2 are the position of each particle respectively. As underlined by Haken et al. (1985), the linear oscillator cannot take into account all the components of a complex behavior. These two equations (2a)

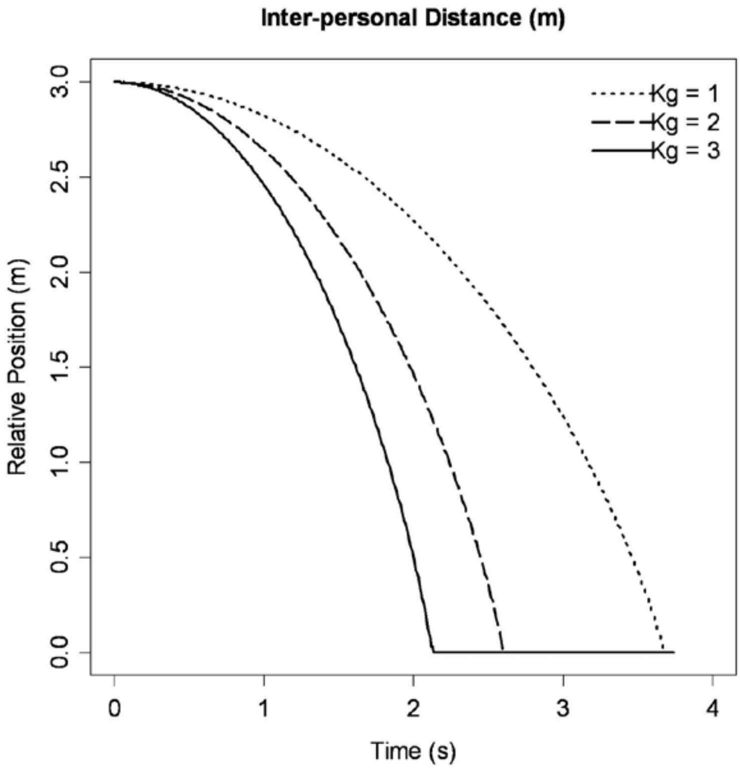

Figure 2 — Gravitational effect. These curves illustrate the effects of Equation (1) only. This figure depicts the gravitational effect on particle displacement depending on the gravitational constant in kg. The acceleration between the two subjects increased depending on the gravitational parameter (kg). This *attraction* parameter could be compared with the "desire" of each subject to attack his opponent. This attraction force is always required to ensure that the main objective of the task is achieved, i.e., attack.

and (2b) lead to an oscillatory movement (see Figure 3). However, this preliminary model uses only the linear oscillator, and the nonlinear behavior will be modeled in a separate set of equations. Using equations (1) and (2), we get a coupled harmonic oscillator describing regular coordination between two particles. This coupled harmonic behavior has already been shown in previous experiments on segmental coordination between two subjects (Schmidt et al., 1999). Figure 3 shows typical simulation data for this kind of model using two different sets of parameters. Linear rhythmical oscillatory behavior is simulated using the coupling equation defined in Section 2.4. These simulation results could be compared with another experiment in which one subject was the leader and the second was the follower (Ducourant et al., 2005). The status of leader or follower is not predefined in a real situation, although many authors have shown that social status could influence this variable (Hediger, 1961). Moreover, the objective of every fight or confrontation

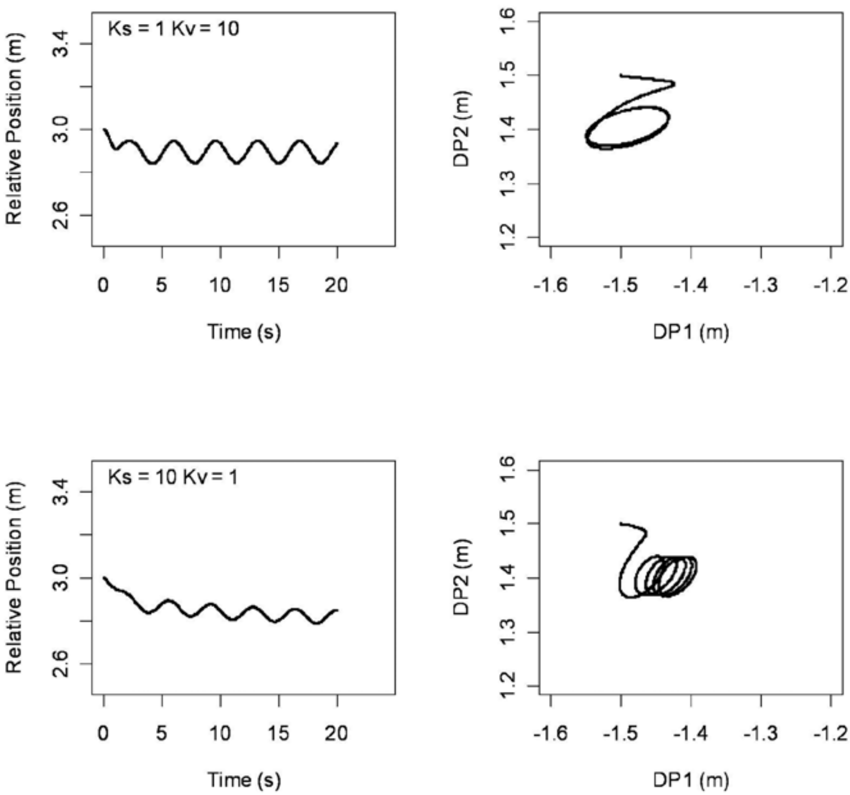

Figure 3 — Oscillatory responses. These curves illustrate the effects of Equations (1) and (2). During the first second, the interaction distance is built up, and this distance is maintaining during the entire simulation time (Equation 1). The oscillatory behavior is fully described by Equations 2a (for particle 1) and 2b (for particle 2). For each equation, stiffness (K_s) and viscosity (K_v) parameters define oscillatory responses. This figure illustrates cases (K_s = 10, K_v = 1 and K_s = 1, K_v = 10). The left panels show the relative position as a function of time. The right panels show the distance of particle 1 from the center (DP1) *versus* the distance of particle 2 from the center. Depending on the stiffness (K_s) and viscosity parameters (K_v), the oscillation produced by the harmonic oscillator could be adjusted to capture the subjects' oscillations.

is to reach one of two solutions: escape or attack. The next modeling phase should consider this aspect.

Decoupling Phase. Our hypothesis is that this last phase (the decoupling phase) is controlled by psychological parameters (decisional and/or emotional). We introduced a new set of equations allowing the model to switch from attraction (coupling harmonic oscillators) to decoupling.

Switching behavior between coordination and decoupling was defined by a continuous variable K_q associated with a discrete variable represented by the sign of K_q (Berg, Wade, & Greer, 1994). This two-state variable defined two different behaviors: $K_q < 0$ meant that the subject's chosen strategy was to *escape* and $K_q > 0$ meant that the subject's strategy was to *attack*. The intensity of these strategies was determined by one variable for each subject K_q and intersubject distance (r). The general form of this interaction is:

$$K_q^i \cdot \frac{q_1 q_2}{r^2} \tag{3}$$

As in Equation (1b), we can define force as an action of particle one (P1):

$$F_q = F_q(r)\hat{x} \tag{3'}$$

where $\hat{x}$ is a unit vector whose direction depends on the location of the subject with respect to the center (C). For instance, P1 attack displacement will be a positive displacement whereas P2 attack displacement will be negative. It is exactly the opposite for the escape situation.

The values K_{q1} or K_{q2} can be modified arbitrarily during the simulation. Figure 4 shows a typical example of simulation data.

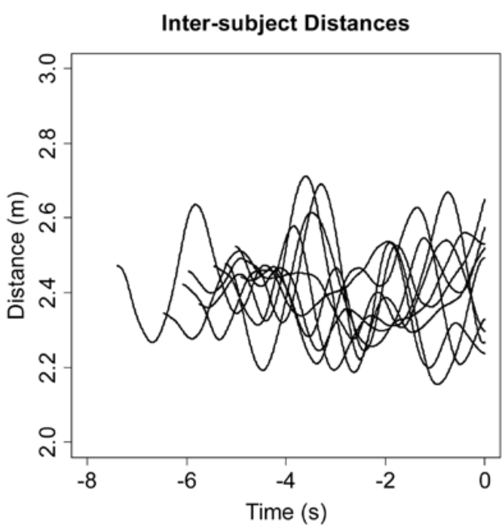

Figure 4 — Interaction response of the coupling and decoupling phase. This figure shows 10 superimposed distance variations as a function of time (fight duration). Time 0 corresponds to the moment of attack. Each curve illustrates the cumulated effects of Equations (1), (2) and (3). Random noise as explained in Equation (6) was also added. Depending on the stiffness (K_s) and viscosity parameters (K_v), the oscillation produced by the harmonic oscillator could be adjusted to capture the subjects' oscillations.

Coupling Equations

A coupling term can be found in our previous equations. For instance, forces produced using Equations (1) and (3) depend on the distance between P1 and P2. So, the first implicit coupling equation could be formalized as:

$$r = x_1 + x_2 \tag{4}$$

where r is the distance between P1 and P2 and x_1 represents the distance between P1 and C, and x_2 represents the distance between P2 and C.

In fact, x_1 and x_2 are constrained by the length of the weapon. We assume that this length is the same for both subjects (L). We can now define each distance by:

$$x_1 = L + \tilde{x}_1 \text{ and } x_2 = L + \tilde{x}_2 \tag{4'}$$

so the total distance between the subjects is:

$$r = 2L + \tilde{x}_1 + \tilde{x}_2 \tag{4''}$$

where $\tilde{x}_1$ and $\tilde{x}_2$ represent the variable part of the distance for P1 and P2 respectively. In this model, we assume that part of this variability is voluntarily introduced by each subject for two reasons: 1) to create an *exploratory signal* to be able to act and react (*Es*) and 2) to capture the random movement of the subject's arm and weapon a stochastic noise (ζ) was added. For each subject we could define *Es* as:

$$Es_1 = a_1 \cos(\omega_1 t + \varphi_1) \text{ and } Es_2 = a_2 \cos(\omega_2 t + \varphi_2) \tag{5}$$

We can replace Equation (4") by

$$r = 2L + a_1 \cos(\omega_1 t + \varphi_1) + a_2 \cos(\omega_2 t + \varphi_2) + \xi \tag{6}$$

In a general way, the subjects could independently produce amplitude (a_i) and frequency (represented by $\frac{\omega}{2\pi}$).

One other implicit coupling equation is contained in Equation (3). The total force produced by Equation (3) depends on parameters from Subject 1 and Subject 2 called decisional parameters (K_{q1}, K_{q2}). The main advantage is that the equation could be used as a coupling or a decoupling equation depending on parameter values.

Nonlinear Effects

The simulation results presented in the previous section did not exhibit an oscillatory behavior. Our present model does not take into account such a nonlinearity component. As emphasized by Haken et al. (1985), nonlinearity must be introduced to stabilize a coupling system. In our model, nonlinearity was introduced by adding noise to the coupling equation (see Equation 6). However, nonlinearity can also be added by introducing physiological noise using a time delay in the coupling equation (Haken et al., 1985; Haken, 2001). In our mechanical model, forces act instantaneously which means that kinematics and the effect of these kinematics produced by one subject are directly perceived by the other subject. In the real world, there is always a time delay between action and perception and between perception and action. So it is possible to apply forces generated by P1 on P2 and by P2 on P1 with a time delay (τ). This last point is not developed in this article and will be implemented in near future. The model could generate acting forces in advance to counteract expected subject dynamics.

Computer Simulation

To calculate all the forces applied to each particle, we used Equations (1), (2a) and (2b), (3) and (6). We solved all these equations on a digital computer using constraint dynamics and library software initially developed by Barenbrug (2000) to change dynamically-controlled parameters. The motion integrator used in this study was a fourth order Runge-Kutta method with an integration step of 0.01 s. For Equation (1), the mass (m_1 and m_2) constant was equal to 60 kg. Figures 2, 3 and 4 show typical simulation results for a set of four different parameter values (K_g, K_s, K_v and K_q).

Actual Data

This study was a preliminary experiment designed only to test the validity of the model.

Method

Three subjects called *kendokas*, members of France's national team (international level) gave informed consent for participation in the experiment, in compliance with the Helsinki Declaration. They were 25 years old ±1.8 years (mean ± *SD*). The mean height of the subjects was 1.78 ± 0.22 m and the mean weight was 75 ± 5.3 kg. All participants were in good health. Thus, we were able to form three fighting pairs.

The experiment was held in a large gymnasium which was equipped with a set of 24 Vicon V8 cameras (Oxford Metrics Ltd). Each subject wore a set of 34 markers for the computation of local and global kinematics. The markers were placed on the head, neck, upper limb, trunk and lower limb. Three markers were also located on each subject's weapon (called a *shinai*). A large square was drawn on the floor (10 m × 10 m) similar to the fighting surface used during Japanese fencing matches. We used only trials in which any gaps in the data collection of the head and the feet positions were smaller than 10 consecutive missing samples (83 ms); these gaps were filled in using a polynomial algorithm. Data were sampled at a rate of 120 Hz and reconstructed in three dimensions. The raw data were processed with a fourth-order Butterworth low pass filter and a recursive filter without phase shift and using a cut-off frequency of 12 Hz.

At the beginning of each trial, the two subjects were precisely positioned face to face in an upright posture. Only the *observation phase* and *attack phase* were investigated.

Model parameters were optimized to compare simulation and actual data. In particular, mean frequency parameter (Equation 6) and initial distance were computed from actual data.

Kinematic Data

Weapon Velocity. The first point that we studied was the transition between the coordination phase and the decoupling phase. The distinction between these two phases has been defined from velocity data. Figure 5 shows an example of the weapon velocity variation. We can easily identify a stable phase at the beginning with little velocity variation which corresponds to the coordination phase. When the fighter decides to touch the opponent, we observe an increase in the velocity variation which corresponds to the excitatory noise intended to induce a reaction from the opponent. The transition between the coordination phase and the decoupling phase is observed at the beginning of the first major peak of velocity on the curve called V_z. Here in this example this peak is produced at 0.9 s and weapon velocity is around 10 m/s.

Intersubject Distance. We were interested here in the coordination phase. We assumed that it was composed of two parameters (see Equation 4): the first composed of a fixed distance (length of the *shinai*) and the second composed of a variable distance (variability induced by the subject). Figure 6 represents the intersubject distance for a fighting set during this phase. In this figure, the trials are not of the same length because we used actual data, and consequently the duration

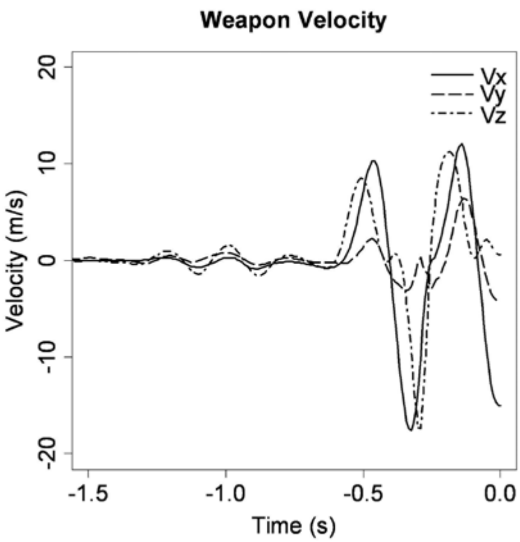

Figure 5 — Weapon velocity. This figure shows the velocities of weapons X, Y and Z during the coupling and decoupling phase. The beginning of the decoupling phase is clearly identified by a velocity threshold on the Z axis. Time 0 corresponds to the moment of attack.

of the trials was not equal. We can see that the distance curves vary around a mean value of 2.387 m (sd = 0.057). The small variations observed represent the play of action-reaction between the fighters to create an opportunity to attack. This actual mean distance seems to correspond to the exact distance defined in Equation (6). In this equation, the *L* parameter defines the weapon length, as determined by the Japanese Federation of Kendo to be 1.18 m. Equation (6) used not L but 2*L (2.36 m) and this distance could be assumed to be equal to the mean actual distance. In a new experiment, we could easily manipulate this parameter in different ways: modifying weapon length for both subjects (increasing or decreasing size) or modifying weapon length independently for each subject.

To compare actual and simulated data (Figure 4 and Figure 6), harmonic analysis was performed on each set of inter subject distances. This frequency analysis showed that the main frequency for all data were 0.510 Hz (sd = 0.219). In our model, this main frequency was 0.543 Hz (sd = 0.213) and was the result of combination of two coupled harmonic oscillators and added constraints (Equation 6). There were no statistical differences between actual and simulated data for amplitude and frequency. This suggests that even in a fighting task, which is not a coordination task by itself, a coupling phase need to be added to model the behavior of each subject. The purpose of this coordination time could be interpreted as phase of information exchange between the two subjects to be able for one fighter to tune the internal parameter K_q to initiate the decoupling phase.

Weapon Relative Position. This play of action-reaction can be also observed when we look at the evolution of interweapon position. As for the intersubject distance, the interweapon positions oscillated around a mean value equal to zero.

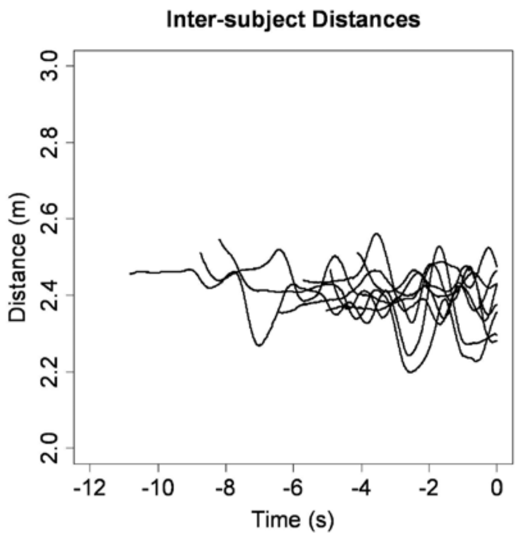

Figure 6 — Intersubject distance variation. This figure shows 10 superimposed distance variations as a function of time (fight duration). Time 0 corresponds to the moment of attack.

These oscillations are the result of two types of dynamics. The first part of this dynamic could be characterized as intrinsic dynamics, generating each subject's arm movements. In our model, these variations are taken into account by Equation (5) and represent the excitatory part created by each subject. The mean frequency of these oscillations is around 2.5 Hz. Of course, this mean frequency corresponds to the simulation results simply because, as mentioned previously, the frequency parameter of Equation (6) was tuned using real data.

The second part is the result of the displacements of the subjects with a movement frequency of around 0.5 Hz and could be the effect of the coupled harmonic oscillator described by Equations (2a) and (2b). Figure 7 shows an example of these variations. The simulated data could be compared with actual data using linear and nonlinear time series analysis. Using such analysis (Hegger, R., Kantz, H., & Schreiber, T., 1999) it should be possible to compare the complexity of each signal (actual data and simulation). For instance, correlation dimension of real data (c = 1.412, sd = 0.238) and simulated data (c = 1.592, sd = 0.212) were not statically different ($p > .5$).

Angle Variations. In Section 2.1, we wrote that the fighters could be represented by particles which move in a one-dimensional space. This means that horizontal displacement could be summarized by a curvilinear trajectory described by the subject's motion. Figure 8 shows the vertical projection angle between two weapons. This interweapon angle could be considered as a constant value (180.5 ± 1.87 degrees). Furthermore, the two-weapon horizontal projection angle curves are correlated ($r = .84$) showing that these results validate our hypothesis of a one-dimensional movement space.

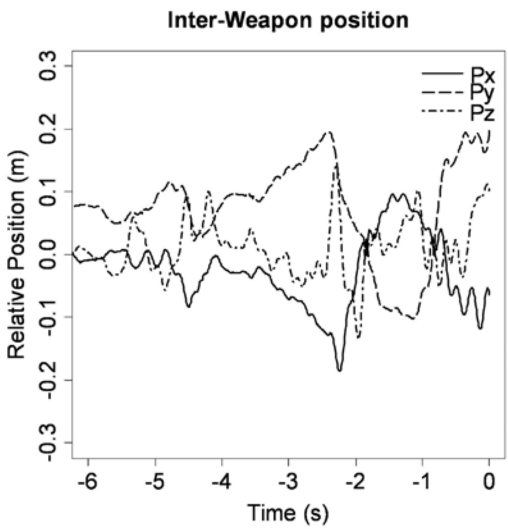

Figure 7 — Interweapon position. This figure shows one subject's relative weapon position in the intersubject reference frame. This reference frame origin is determined by the center C (see Figure 1). Time 0 corresponds to the moment of attack.

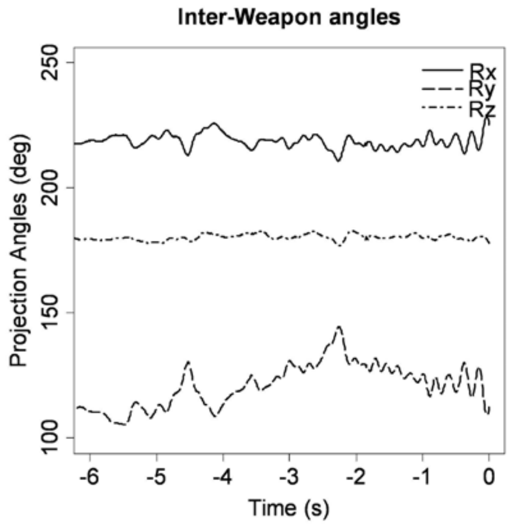

Figure 8 — Interweapon angles. This figure shows interweapon orientation. Rx corresponds to the transversal rotation, Ry antero-posterior axis and Rz is the vertical axis.

Discussion

In this paper, we present a general model for interpersonal interaction. These kinds of general models have already been developed for everyday behavior (Sprott, 2004, 2005). Such simple linear models added to nonlinearity could produce either stable oscillations or chaos depending on internal and external conditions. Following the same philosophy, the aim of this study is to develop a simple model of *natural* interaction using linear coupling equations and adding nonlinearity using time delay or noise. The main assumption is that complex behavior could be modeled and probably explained by simple features. Furthermore, our model could simulate three general phases of human interaction: 1) the approach or preparation phase 2) the coupling phase and 3) the de-coupling or chaos phase.

Preparation and Decoupling Phases

In this model, we specifically introduced three types of equation. The first Equation (1) is related to the attractive force between two subjects. This force is revealed during the preparation and decoupling phases. This "gravitational" force is associated with a similar type of force represented by Equation (3). The main difference between these two interactions is that in Equation (3) the direction of the forces is determined by decisional and/or emotional parameters. To summarize, the interaction form is:

$$\frac{K.D(x)}{r^2} \tag{7}$$

where K is a general constant corresponding to the intensity of attack and $D(x)$ is a decisional parameter depending on the subject himself (emotional aspect) and the subject's position (x_i). This last parameter $D(x)$ could compensate for the attraction forces to prevent an automatic crunch of the two particles contained in Equation (1). However, we preferred to specify two different equations corresponding to different control parameters to manipulate these parameters during simulation or actual experiments. For instance, it should be possible to propose that the gravitational parameter (Equation 1) be represented by task constraints. During a fencing task, there is an implicit instruction: to move toward the target. Our preliminary results have shown that displacement during the last decoupling phase is parabolic as described by Equation (1) and Equation (7).

Coupling Phase

The coupling phase is modeled using Equations (2a), (2b) and (6). Using these three equations during simulation and adding nonlinear effects leads to a nonlinear coupled oscillator. This kind of model, using the Van der Pol equation, has already been used to simulate intersubject coordination during opposition (Freslier, Ducourant, Slotine, Flash, & Berthoz, 2004). In Equation (6), the base line is determined by a constant value: 2L. In real experiment L, the parameter is directly correlated to the weapon length. Weapon length is standardized at 1.2 m. According to our model, it is not surprising that the mean critical distance is 2.4 m (2.387 ± 0.057 m). However, actual data shows that two main frequencies could be extracted from interweapon position (see Figure 7). In this case, we decided not to use Van der Pol equations to simulate oscillations. Our hypothesis is that two oscillators are superimposed with two different frequencies. The first one is represented by the linear harmonic coupled oscillator as described by Equations (2a) and (2b) with an additional nonlinear effect. This oscillatory behavior corresponds to the low frequency component of actual data. The nonlinear part of this equation was implemented using random noise. However, such a linear effect could be due not only to stochastic noise, but to *internal* nonlinear dynamics from the subject himself. This *intentional* noise should be generated by the subject to hide his dynamics or to trap the opponent.

As we mentioned previously, time delay was not implemented in this first model and force is acting instantaneously. This time delay parameter should be developed in a future version of this model. Adding time delay will introduce a nonlinear component, but the main advantage is that the time delay parameter could model anticipation. In fact, if we consider that a positive time delay measures the time between action and perception, a negative time delay could represent anticipation.

Decoupling Phase

Decoupling means that the critical distance established during the coordination phase is destroyed by two main behaviors: one subject becomes a predator and the other becomes a prey. In our model, we hypothesized that a discrete parameter K_q called the decisional or emotional parameter could introduce chaotic behavior leading to rupture. In this case, the distance between the two subjects decreases up to zero.

This chaotic phase should exhibit specific behavior such as kinematic instability when subjects are close to the rupture phase. In real data, this instability could be measured in term of kinematics (velocity or relative distance) and/or change in complexity. However, this assumption was not tested in this article even though all subjects seem to show increasing instability in their kinematics. In fact, this experiment was initially designed to validate the two first phases and a new experiment will have to be designed to test this specific phase.

Conclusion

In conclusion, this preliminary study suggests that a simple modeling approach could be used to characterize a complex human interpersonal task or interaction without modifying or restraining the task itself. However, this model first needs to be more precisely validated by adding more subjects and data and using more experimental conditions related to model parameters. For instance, this model defined three dimensions depending on 1) task constraints 2) dynamics of the subjects and 3) decision and emotion of the subjects. Each dimension corresponds to one control parameter and should be investigated independently. Furthermore, it would be interesting to develop an extended version of this model for general human interaction tasks or opposition tasks.

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