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Drum Roll: Increasing Bandwidth Through Passive Impedance Modulation

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Abstract

Skilled drummers can play drum rolls at frequencies well in excess of human motor control bandwidths, by allowing the drumstick to bounce passively against the drum head at least twice for each hand stroke. We present experimental evidence that drummers modulate grasp force to control the effective stiffness of the drumstick, which in turn determines the bounce frequency. To confirm this explanation, we constructed a simple, single-joint robot that emulates the human drumming technique. McKibben "artificial muscle" pneumatic actuators are paired in an agonist-antagonist configuration, resulting in a slow robot with variable passive impedance. The robot can execute drum rolls across a frequency range comparable to human drumming (bounce interval = 40 -160 ms). The results demonstrate that modulation of passive impedance can permit a low bandwidth robot to execute certain types of fast manipulation tasks.

1 Introduction

People can accomplish many high bandwidth tasks despite the slow response of the neuromuscular system. Reaction times are about 130 ms for tactile or auditory stimuli, and over 150 ms for visual input (Boff and Lincoln 1988). The fastest human responses are due to hard-wired reflexes, which can help to maintain limb posture in response to specific disturbances (McMahon 1984). Even the fastest of these, the stretch reflex, does not begin to act until 20-30 ms after a limb is displaced. Faster responses are precluded by slow nerve conduction velocities, usually well under 100 m/s.

Despite these limitations, skilled drummers can play a drum roll at over 40 Hz. Drummers take advantage of a passive dynamic interaction: they let the drumstick bounce against the drum head at least twice on each hand stroke. The bounce occurs too quickly for changes in muscular control to have a significant effect, so the parameters that govern the interaction must be predetermined. In this paper, we present evidence that drummers vary the stiffness of their hands to control the bounce frequency. The drum roll is thus an example of the explicit use of impedance modulation to increase effective bandwidth in a manipulation task.

To confirm this explanation, we have constructed a simple robot joint that performs a drum roll in much the same manner as a human drummer. In contrast to "active" impedance control, which requires a fast servo loop, our robot uses slow pneumatic actuators. These actuators can, however, modulate passive joint stiffness as well as position or torque. Our experiments show that drum roll frequency can be controlled by varying the robot's passive stiffness, as surmised for human drummers. The results also demonstrate that inexpensive robots with passive stiffness control can compensate for low bandwidth in some manipulation tasks.

1.1 Human motor control

A number of mechanisms help compensate for long neuromuscular response times. One method is ballistic or anticipatory control (Johansson and Westling 1988). In some tasks, a rapid sequence of motor commands may be sent to the muscles to produce successful interactions without the need to process and respond to sensory input. A common example is playing a fast musical passage on the piano, where there is insufficient time for feedback from the fingers and ears to influence the muscle commands before the key stroke is completed. Repetitive practice of such tasks allows conscious use of sensory information to perfect the required motor commands, which are then "played back" through the muscles to accomplish the task. This approach works well only if the interaction with the environment is predictable.

Faster or less predictable interactions may often be controlled by varying the mechanical impedance of the limb. Muscle stiffness increases in proportion to the force it is generating (Winters 1990). Since muscles are generally arranged in agonist-antagonist configurations at each joint, muscle pairs may be co-activated to increase the stiffness of the joint without changing the net torque output or position of the joint. With an appropriate endpoint impedance, the passive interaction with the environment can produce the desired behavior (Hogan 1985). For example, downhill skiers use their legs as variable impedance springs. By varying leg kinematics (knee and hip joint angles) and muscle co-activation level, the effective stiffness between the ground and the body can be modulated. This allows the skier to rapidly descend a hillside covered with diverse bumps that are traversed too quickly for independent reaction.

While the importance of impedance modulation is widely acknowledged, its functional role is not entirely understood. A number of researchers have studied lower limb impedance, and impedance modulation is now an accepted part of the elucidation of legged locomotion in both humans (McMahon 1984) and robots (Raibert 1986; Pratt and Williamson 1995; Berkemeier and Desai, 1996). For the human upper limb, studies have measured arm and hand impedance, but there is little work on how impedance modulation relates to manipulation task execution. There are, however, a number of common tasks where this is clearly important. One example is catching a ball, especially when the incoming speed or exact location is uncertain; a football receiver must have "soft hands" or the ball may bounce away before it can be securely grasped.

1.2 Robot impedance control

In robotics research, modulation of arm impedance has been the focus of a great deal of activity. The most common approach, active impedance control, uses sensors and actuators linked with a computer controller in a fast feedback loop (e.g. Salisbury 1980, Mason 1981). Although this active control can produce a wide range of impedances, sensor inaccuracies and servo loop delays can vary the actual endpoint impedance, and contact with hard surfaces can cause instabilities (Colgate 1989). These factors tend to increase the cost and limit the range of application of this scheme.

The alternative approach, passive impedance, generates the selected impedance without sensors or controllers, and avoids the limitations these components entail. The remote center of compliance (RCC) wrist is perhaps the best-known example (Whitney 1982), but it is specialized for a single task. For programmable passive impedance, a number of researchers have presented devices to be used in combination with traditional robot actuators. These include variable compliance wrists (Cutkosky and Wright 1984) and hybrid elements for inclusion in robot drive trains (Mills 1990; Laurin-Kovitz et al. 1991) or structures (Immega and Antonelli 1995). This approach can combine the advantages of passive impedance and high bandwidth, but there is concomitant increase in cost and complexity of the manipulator system.

In contrast, we present a robot joint whose actuators have low bandwidth but variable passive impedance. This is essential to our immediate goal of confirming that the inferred human strategy – slow modulation of passive hand impedance – is sufficient to explain the observed fast drumming performance. In the following section, we begin with experimental characterization of human drum rolls, and present a model that relates grasp force to drumming frequency. Next we describe the design of our robot joint, including careful characterization of its McKibben muscle actuators (Chou and Hannaford, 1996). We then perform drum rolls with this robot and demonstrate the expected relationship between joint stiffness and drumming frequency. Finally, we discuss implications for more general robot tasks and the challenges of impedance selection.

2 Human Drumming

Many different techniques are used to produce fast, continuous drumming. Here we focus on the standard double stroke roll practiced by trained drummers. Although it is not necessarily the technique that maximizes bandwidth, it embodies the passive dynamic interaction of interest, and it is straightforward to measure and analyze. We also limit our consideration to the mechanics of one hand and drumstick, and ignore the bimanual coordination issues. The double stroke roll begins with one hand striking the drum with the stick, which is then allowed to bounce once. As this stick is retracted, the other hand brings its stick onto the drum for the next double stroke. This alternating sequence of double bounces is repeated for the duration of the roll to establish a steady drumming frequency.

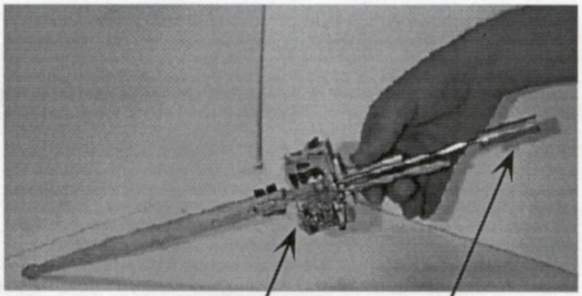

Figure 1. Instrumented drumstick

To analyze this process, we must reduce its kinematic complexity: as in virtually every manipulation task involving the hands, the number of links and degrees of freedom is unwieldy. Thus we videotaped trained drummers and conducted preliminary experiments to determine the salient factors across the range of drum roll frequencies. Drumming is a creative activity, and although there is no universal convention for holding a drum stick, a common method is to grasp the stick between thumb and index finger about two-thirds of the length away from the contact tip (Figure 1). The other fingers act to support the proximal end of the stick and control its height following a stroke. We determined that during the double bounce, the arm and hand are basically motionless, and the dynamics of the fingers-stick-drum system govern the passive bounce. Furthermore, the stick essentially pivots about a point between the finger and thumb, which approximates a constant center of rotation of the stick during interaction with the drum; presumably this minimizes reaction forces transmitted to the drummer though the hands.

2.1 Passive Bounce Model

Based on our observations, we propose a simple lumped-element second order model to represent the fingers-stick-drum system during the interaction (Figure 2). The drum head is represented by a massless spring and damper, while the stick is modeled as an equivalent translational mass at the tip, including contributions from the finger and thumb mass. This stick-and-finger mass is coupled to the rest of the hand through the variable joint impedance of fingers, represented by a spring and damper. The hand position is essentially fixed during the interactions with the drum, and is then retracted across longer time scales by wrist and/or arm motion. While the stick is in contact with the drum, the model on the left side of Figure 2 is valid; while the stick is in free-flight during the passive bounce, the right side pertains.

Drumming frequency can be described by the bounce interval, the time between the two contacts with the drum head. Our measurements suggest that the finger-stick system

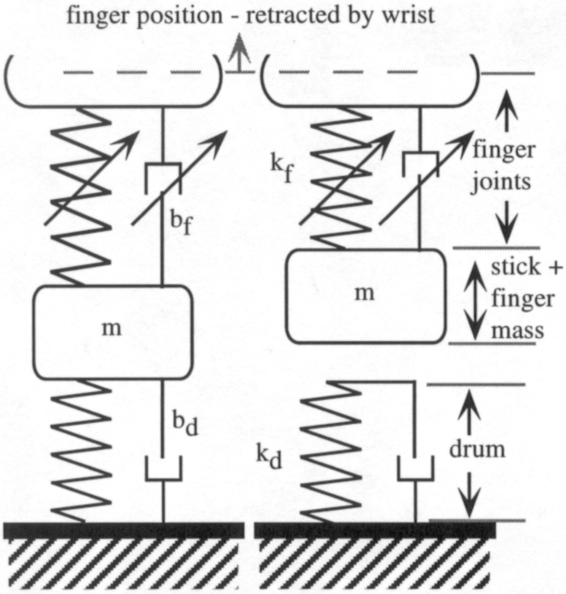

Figure 2. Lumped element model of hand-stick-drum system during drum roll bounce

is strongly underdamped, so for simplicity we neglect damping. From the model of Figure 2, the bounce interval should be proportional to the natural frequency $\omega_{bounce} = \sqrt{k/m}$, where k is the stiffness of the fingers, and m is the effective mass of the finger-stick system. Since muscle stiffness increases in proportion to the force generated (Winters 1990; Hajian and Howe 1994), modulation of the grasp force between the finger and thumb allows the drummer to control k (Hajian and Howe 1996). This relationship shows how voluntary modification of grasp force directly controls drumming frequency.

2.2 Human drumming data

To experiementally confirm this model, we recorded grasp forces and drum head impacts as skilled drummers played double stroke rolls at a range of frequencies. The instrumented drumstick shown in Figure 1 consists of the forward half of a wooden drumstick rigidly connected to strain gauge force sensors that measured forces on the finger and thumb. To maintain realisitc kinematic coupling between the hand and the stick, the grasping surface had the same curvature as the unmodified drumstick. A counterweight balanced the inertia of the force sensors, and although the weight of the apparatus was significantly greater than a standard drumstick, subjects had no difficulty drumming in the usual manner. The drumming surface was a section of a rubber drum practice pad; a piezoelecric force sensor underneath this pad measured impact forces.

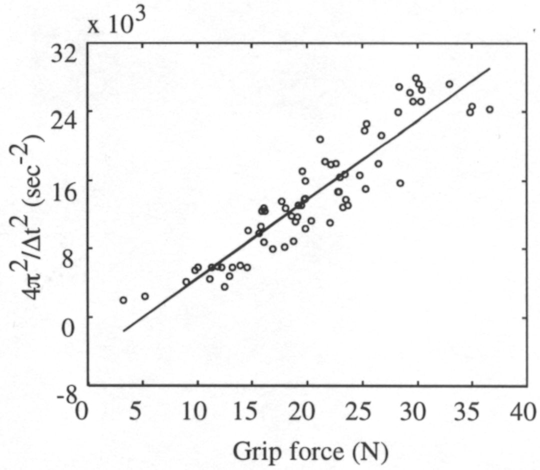

Figure 3. Bounce frequency squared $(\omega)^2$ vs. grasp force

Measured bounce durations ranged from 30 to 140 ms, and grasp forces from 3 N to 36 N. Figure 3 shows typical data for one drummer for strokes with peak impact forces between 34 and 42 N. The square of the bounce frequency, $\omega_{bounce}^2 = (2\pi/\Delta t_{bounce})^2$, is plotted against the grip force, measured at the thumb. From the relationship above, the stiffness should be proportional to ω_{bounce}^2, and the measurements are in fact grouped along the best fit line. Overall, the data shows the expected correlation between grasp force level and drumming frequency predicted by the model.

3 Robot Drumming

To confirm the human results, and to demonstrate fast task execution using passive impedance, we constructed a simple robot joint and used it to perform a drum roll. The robot uses McKibben "artificial muscles," which are configured as low bandwidth actuators with variable passive impedance. By using two of these devices in an opposing agonist-antagonist configuration, a single joint can both reset the drumstick position for each stroke, and set the passive joint impedance.

McKibben muscles are comprised of an internal rubber bladder surrounded by a cylindrical braided mesh (Chou and Hannaford 1996). Fabrication of the actuators from inexpensive materials is straightforward (Hannaford 1996). When the inner bladder is inflated, it bulges and shortens to a new rest length while contained by the braided mesh. The stiffness in tension increases with increasing pressure, approximately doubling over the pressure range tested. Specific stiffness values can be achieved by varying the dimensions of the muscle. We used 4.0 mm inner diameter silicone rubber tubing with a 0.8 mm wall thickness, and 12.7 mm diameter braided mesh sheathing.

Figure 4 depicts the force measured during imposed lengthening of a McKibben muscle at various constant pressures. The best fit slopes of these lines show a twofold increase in stiffness, from about 4.2 N/mm at 25 psi to about 8.4 N/mm at 75 psi. The intercepts along the horizontal axis indicate the rest lengths, shorter with increasing pressure, at each of the six pressures where we characterized the muscle stiffness. The shaded area in Figure 4 indicates the range of muscle lengths used in the final robot joint design. This range allowed the greatest span of working pressure, and hence usable stiffness. Many fabrication parameters can be

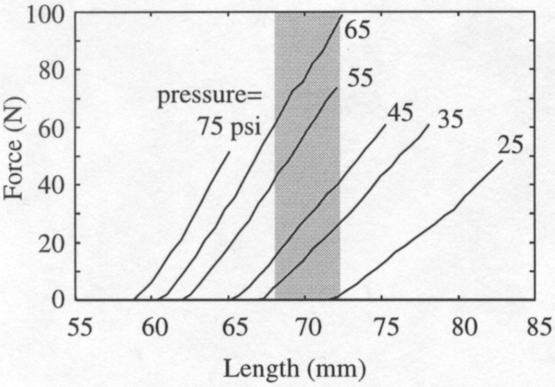

Figure 4. McKibben muscle stiffness characterization: tensile force vs. muscle length

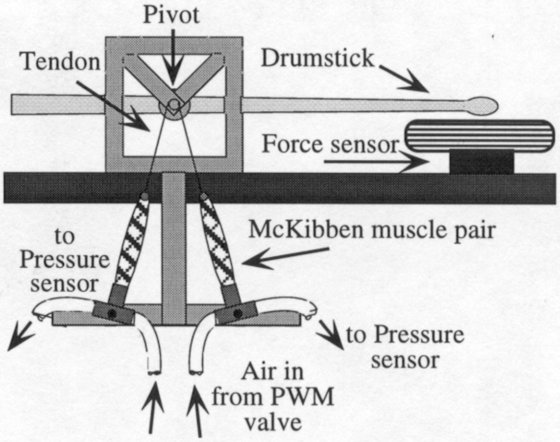

Figure 5. Drumming robot apparatus

arbitrarily varied; we selected the working pneumatic volume, the size and length of the muscles, and the dimensions of the robot joint to result in stiffnesses variation and resultant bounce frequencies comparable to those observed in the human drumming experiments.

3.1 Design of the Drumming Robot

Figure 5 shows the robot drummer. As in many physiological systems, the agonist-antagonist configuration allows independent control of both the net joint stiffness, and the joint position or torque. The muscles are attached to opposite sides of a shaft with a Kevlar tendon. A drumstick is rigidly coupled to the shaft so that it rotates about approximately the same point as in human drumming. A quartz piezoelectric force sensor measures the impact forces of the stick onto a drum pad.

Since low bandwidth was a design goal, the air flow into each muscle is controlled by an inexpensive solenoid valve. These valves were pulse width modulated (PWM) at 130 Hz, and the pressure in each muscle can be controlled between 0 and 75 psi gauge, with peak-to-peak ripple less than 6 psi. To match the filling and emptying rates of the muscles at the selected operating point, the outlet of the solenoid valve exhaust port was reduced to a 1.1 mm diameter.

3.2 Reset Actuation

Actuation of the drum stick by commanding differential pressure changes in the muscles corresponds to the action of the wrist or arm in lifting the stick away from the drum after a stroke. Figure 6 shows time records of five parameters which demonstrate the actuation speed of the robot. The plots show the drumstick moving in free space (not in contact with the drum pad) moving through a tip displacement of about 53 mm. The first two traces depict the complementary square wave command inputs (C1 and C2) to the PWM circuitry for each solenoid valve. The specified operating set point of the drum stick is the equilibrium position with a pressure of 42 psi in each muscle. The next two traces show the pressure in each muscle (P1 and P2) as measured by solid state pressure sensors. Pressure decreases in muscle 1 to about 36 psi, and increases in muscle 2 to about 50 psi. This change in pressure

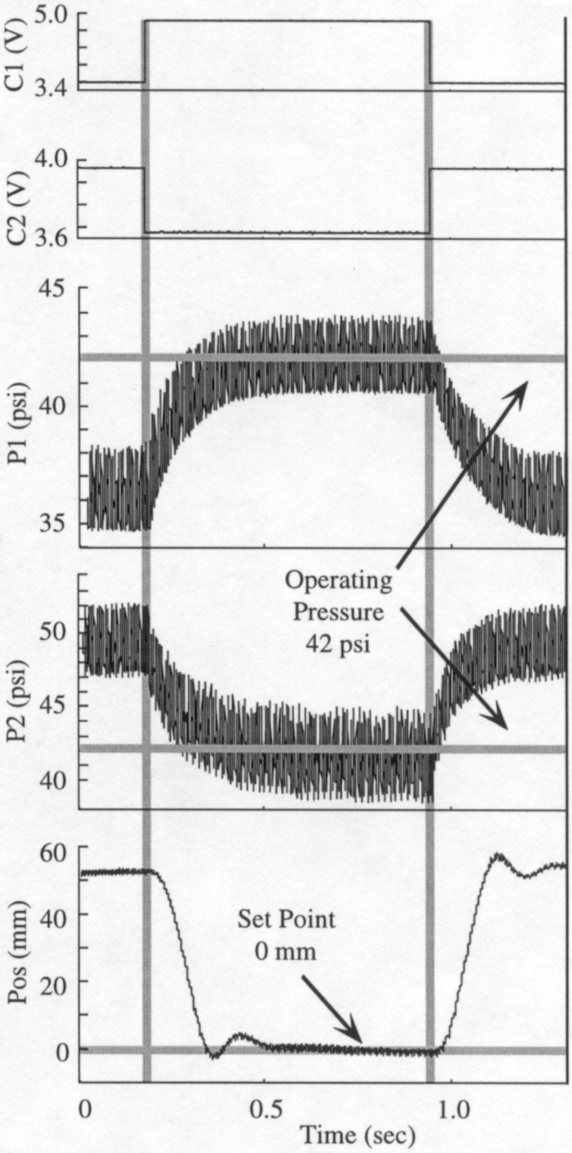

Figure 6. Reset actuation bandwidth

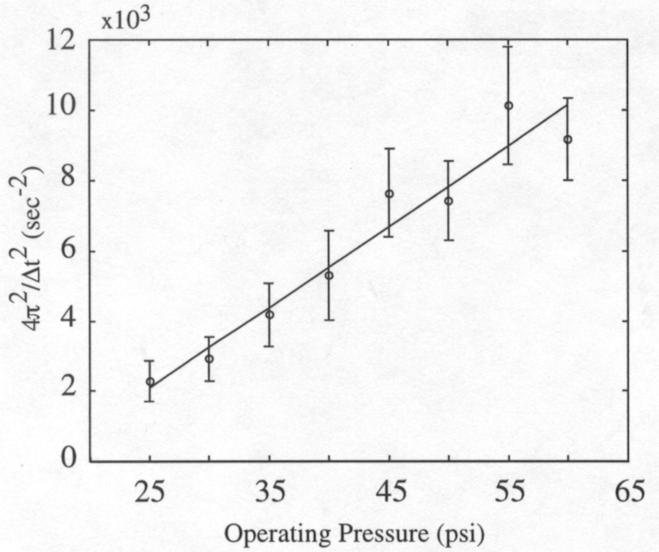

Figure 7. Bounce frequency squared $(\omega)^2$ vs. muscle pressure

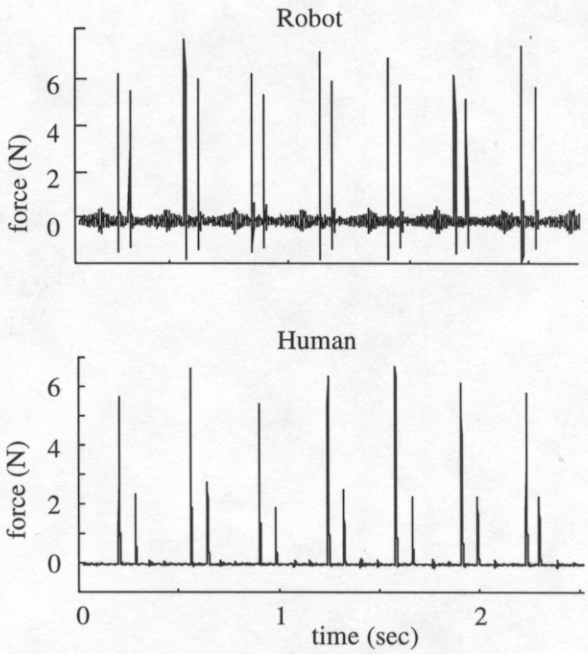

Figure 8. Drum roll comparison: robot vs. human

moves the equilibrium point of the drum stick, while maintaining approximately the same stiffness. The system stiffness is unchanged because the muscles are in a parallel configuration, and one muscle increases in stiffness roughly as much as the other diminishes.

The final trace shows the displacement (pos) of the tip of the drum stick moving about 53 mm from the original set point. At this operating point, the fall time (10%-90%) was 93 ms, following a 30 ms delay from the commanded inputs, while the rise time (10%-90%) was 91 ms following a 23 ms delay. In addition, each overshoot measured about 2.4 mm (4.5%). Stick movement is relatively smooth, despite the large pressure ripple; the 130 Hz PWM pressure oscillations are in phase in both muscles and thus cancel, and the inertia of the robot and stick also act as low-pass filters. This measurement characterizes the bandwidth only for the given operating conditions, because the system response is affected by many variable and nonlinear factors, such as pneumatic volume, tip displacement, operating pressure, and commanded pressure variation in each muscle. The measurement does, however, show that the bandwidth is roughly comparable to the human bandwidth, and is lower than required for active control of each stroke in the drum roll.

3.3 Robot drumming data

When stiffness control was combined with reset actuation of the stick, the robot drummed very much like one hand of a human drummer. The reset actuation pulse commenced immediately following the second of two bounces, so that the drum stick retracted several cm from the pad before the subsequent passive bounce cycle. Figure 7 shows the range of drum roll frequencies observed, plotted as the square of the bounce frequency, $(2\pi/\Delta t_{\text{bounce}})^2$, as a function of the operating point pressure in the muscles. Error bars indicate the standard deviation of the 8-12 data points at each pressure. The plot shows a linear relationship between the square of the bounce frequency and the set point pressure. From the muscle characterization data above, the pressure is approximately proportional to the stiffness. Thus, as in the human data in Figure 3, the bounce frequency squared varies with the effective drumstick stiffness.

The range of bounce frequencies observed is significantly larger than predicted by the single degree of freedom model. The muscles showed only a 2:1 variation in characterization tests, which should produce a similar range of bounce frequencies squared. Instead, the variation was approximately 4:1. This may be attributed chiefly to changes in the structural stiffness of the robot joint. As the pressure increases in both muscles, forces on the tendons, shaft, bearing, and supporting frame all increase. This results in a higher effective tip stiffness, and a higher bounce frequency. In addition, secondary factors such as the impact force and muscle strain levels were not precisely constant across all pressure levels.

Figure 8 shows time series impact force plots of two drum rolls, one performed by a human and the other by the robot at a similar frequency. The characteristic double bounce is clearly similar in both cases, although the human data shows a great decrease in amplitude for the second bounce. This is probably due to damping in the soft tissue of human finger pads and in the instrumented drumstick, with its composite metal/wood construction.

4 Conclusions and Future Work

Modulation of impedance has long been recognized as an important means of controlling interactions for both humans and robots. In this study, we have attempted to demonstrate that one of the merits of impedance modulation is the ability to increase bandwidth in certain tasks. The human drumming data indicates that controlling hand impedance allows drum rolls at rates well above the conventional limit of the neuromuscular system. The robot drummer confirms that the combination of variable passive impedance and low bandwidth is sufficient for fast drumming, and demonstrates that pneumatic muscle actuators, often characterized as inexpensive but slow, have properties which can transcend the apparent speed limitation.

Although our robot can clearly play a drum roll, it is not likely to replace electronic drum machines. It is intended as a test-bed for demonstrating that drumming is one real task where impedance modulation is important. Determining the role of impedance control in general tasks has proved problematic in both robotics and biomechanics. Passive impedance promises to be most useful in situations involving contact transitions and impacts, where servo loop delays are most problematic. Cost-conscious applications may also benefit, as sensing requirements are minimized and controllers and actuators may be slower and less expensive. In addition, "soft robots" based on passive impedance might prove useful in tasks where robots contact humans, as the danger of large contact forces is greatly reduced.

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