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A robotic apparatus that dictates torque fields around joints without affecting inherent joint dynamics

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ABSTRACT

This manuscript describes how motor behaviour researchers who are *not* at the same time expert roboticists may implement an experimental apparatus, which has the ability to dictate torque fields around a single joint on one limb or single joints on multiple limbs without otherwise interfering with the inherent dynamics of those joints. Such an apparatus expands the exploratory potential of the researcher wherever experimental distinction of factors may necessitate independent control of torque fields around multiple limbs, or the shaping of torque fields of a given joint independently of its plane of motion, or its directional phase within that plane. The apparatus utilizes torque motors. The challenge with torque motors is that they impose added inertia on limbs and thus attenuate joint dynamics. We eliminated this attenuation by establishing an accurate mathematical model of the robotic device using the Box–Jenkins method, and cancelling out its dynamics by employing the inverse of the model as a compensating controller. A direct measure of the remnant inertial torque as experienced by the hand during a 50 s period of wrist oscillations that increased gradually in frequency from 1.0 to 3.8 Hz confirmed that the removal of the inertial effect of the motor was effectively complete.

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1. Introduction

In coordination studies, torque fields acting about joints are one of the factors which influence observed behaviour. Yet, it is normally difficult to manipulate torque fields without also varying other important factors, such as plane of motion, posture, or the perceptual qualities of the produced pattern of coordination. It is also difficult to manipulate torque fields for one limb without also changing them for other limbs. As a result, separation of the effects of these various factors, and discovery of the true causes of certain observations may remain beyond reach. An instrument which allows the setting of torque fields around limbs independently of one another, independently of posture and of the plane of motion, and without interfering with the inherent dynamics of joints would therefore be a useful experimental aid in the study of coordination.

For example, we have recently used such an apparatus for the right wrist, to explore the familiar experience of tapping in time with a favourite tune, during which the downward phase of the gesture invariably coincides with the beat of the music (Carson, Oytam, & Riek, 2009). We were able to demonstrate that the propensity to move down on the beat arises not because of the much hypothesized perception and cognitive internalization of the direction of terrestrial gravity as an ecological invariant, but simply as a result of its immediate inertial effect on the stability and economy of action. In half the trials, we used the apparatus to create a *net* torque around the wrist which was equal in magnitude and *opposite in direction* to the gravitational torque. In other words, in these trials we created an artificial gravity that had the same magnitude as terrestrial gravity, except it pulled *up* rather than *down*. If the tendency to move down on the beat stemmed from a structural internalization of the orientation of terrestrial gravity, then temporarily altering the net torque about the wrist should have no or minimal effect on coordination. If, on the other hand, it stemmed from the downward movement being assisted by the net torque, then the reversal of the net torque should significantly influence the stability of synchronization. In its strongest sense, the latter hypothesis would predict that synchronization would reverse (to moving up on the beat) with the reversal of the net torque. In those trials where we used the apparatus to match the magnitude of terrestrial gravity but reverse its direction, it was the upward phase of the gesture that coincided with the beat for all participants without exception.

In this manuscript, we describe the apparatus that enables torque fields around a single joint per limb to be specified without otherwise interfering with the dynamics of that joint. For a device of its kind, it is based on relatively accessible control theory concepts some of which are familiar to the research community, and it does not require the user to compute typically complex equations of motion. The apparatus utilizes an electric torque motor attached to an interface – e.g., a handle, or a pedal depending on the limb. For simplicity, we will refer to the interface as the "handle". The primary technical problem is that while it is natural to use a torque motor to generate torque, the means of coupling the limb – i.e., a motor-handle system – is far from not interfering with the dynamics of the limb. In fact, if left uncompensated, the coupling imposes added inertia on the limb and attenuates the joint dynamics. This is due primarily to the inherent characteristics of the torque motor, but also to the mass of the handle. This attenuation is particularly troublesome in interlimb coordination tasks, where high frequency oscillations of the limb are typically of particular interest. The higher the movement frequency, the more pronounced the attenuating effect of the motor-handle system. The technical challenge is to control the motor in such a way that we maintain its torque generating capacity while eliminating its attenuating effect on the inherent joint dynamics. In order to manipulate single joints on multiple limbs in parallel, the methods described here are repeated on multiple motor-handle systems.

Our toolset for the task includes a desktop computer equipped with Matlab/Simulink (Mathworks, Natick, MA, USA) software package coupled to a real-time controller board (dSPACE, Paderborn, Germany) which controls the AC servo-motor (Baldor BSM 4250AA, Fort Smith, AR, USA). The sampling rate of the controller board is 200 Hz. The basic function of the motor is that it takes an input signal in volts, $v_\tau(t)$, and produces torque in Nm which is equal to $v_\tau(t)$ multiplied by a scalar $(1/k_{\mathrm{NmtoV}})$ which we know in advance. Essentially, we control the motor by determining $v_\tau(t)$. The control of the motor is formulated in a high-level graphical language in Simulink. The Real Time Workshop feature of Matlab translates the Simulink design into machine code, which gets downloaded onto the