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TECHNICAL NOTE

RELATIVE PHASE QUANTIFIES INTERJOINT COORDINATION

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Abstract—This note illustrates by example how expression of joint movement on a phase plane can quantitatively describe multijoint coordination during complex actions. Automatic digitisation of high-speed video records was used to obtain lumbar vertebral, hip, knee and ankle joint angular kinematics in the sagittal plane of a subject performing a symmetric two-handed lifting movement. A consistent proximal-to-distal coordination was illustrated via angle–angle and relative phase angle presentations. During bending to pick up a load, the joints began their movement in the order proximal to distal while the reverse order of joint involvement occurred during extension. Phase angle relationships between joints may provide sufficiently sensitive measurements to identify changes in multijoint coordination induced by alterations in task variables such as (in the case of lifting) object mass, lifting height and load moment. Information regarding multijoint coordination is likely to be important in attempting to understand the respective roles and interaction between the bi and monarticular muscles which are involved in everyday complex actions like lifting.

INTRODUCTION

Conventional angular-position-time graphs frequently present complex and confusing quantitative descriptions of interjoint coordination in everyday actions. This note compares such methods for the presentation of kinematic data with a method in which the movement of joints is expressed on a phase plane and coordination is quantified by calculating the relative phase angle between joints as a function of time. The example chosen is the coordination of the lumbar vertebral, hip, knee and ankle joints during a lifting task.

METHOD

A high-speed video recording was made of a symmetric two-handed lift performed by an 18-year-old male subject (height 176 cm, weight 69 kg) who had no history of back complaint and no experience in industrial lifting tasks. This subject lifted an 8.5 kg weight with dimensions $155 \times 345 \times 200$ mm. The lift consisted of starting from a normal upright standing posture, flexing to pick up the mass from floor level, then returning to an upright position with the mass held in a carrying position at waist height using a self-selected technique.

Kinematic data were obtained by placing nine spherical reflective markers (30 mm diameter) on the subject in the following locations: spinous process of the first thoracic vertebra (T1); left anterior superior iliac spine (ASIS); left posterior superior iliac spine (PSIS); superior point of the left greater trochanter (GT); the lateral surface of the left thigh on a line joining the greater trochanter to the centre of the knee joint (FEMUR); left lateral malleolus; the lateral surface of the left shank on a line joining the lateral malleolus with the knee joint centre; left fifth metatarsal; dorsal surface of the left hand. These markers were used to define lumbar vertebral, hip, knee and ankle angles. The use of markers on T1, PSIS, ASIS, GT and FEMUR to separate pelvic and lumbar vertebral movement has been radiographically verified (Kippers, 1990; Kippers and Parker, 1989). All angles were defined as included angles which decreased during flexion. Hip angle was defined as the anterior angle subtended between the line joining PSIS and ASIS and the extrapolated line of the femur (as defined by FEMUR and GT markers). Hip angle, thus, became negative in extreme flexion. Lumbar vertebral angle was defined as the anterior angle subtended by lines joining T1, PSIS and ASIS markers.

The subject's movements were recorded at 200 Hz using a video camera and recorder (NAC Inc., Tokyo, Japan) (12 mm lens, f11, 4.5 m from the plane of movement, 0.95 m vertical height). A 1000 W spotlight placed behind the camera caused the markers to contrast with the background. The tape was replayed through a video processor (VP110, MOTIONANALYSIS Corporation, California, U.S.A.) which identifies the pixel coordinates at which transitions occur between light and dark regions and relays these coordinates to PC-based FLEXTRAK software (MOTIONANALYSIS Corporation, California, U.S.A.). The centroids of these outlines were calculated for every second video field, giving an effective frame rate of 100 fps. Customised software was written to calculate the angular position and angular velocity of lumbar vertebral, hip, knee and ankle motion. The angular position data were Butterworth-low-pass-filtered with a 6 Hz cutoff to remove high-frequency noise. This cutoff has previously been chosen as optimal for manual lifting tasks (Kromodihardjo and Mital, 1987).

RESULTS AND DISCUSSION

A conventional angular position vs time presentation (Fig. 1) suggests that flexion and extension of knee, ankle, lumbar vertebral and hip joints occurs more or less simultaneously, a typically preferred mode of coordination in many human movements. However, an alternative analysis of the data reveals a slightly different interpretation, i.e. systematic deviations occur from simultaneous in-phase coordination of the joints.

Figure 2 illustrates the coordination between knee and hip joints by plotting hip angular position as a function of knee

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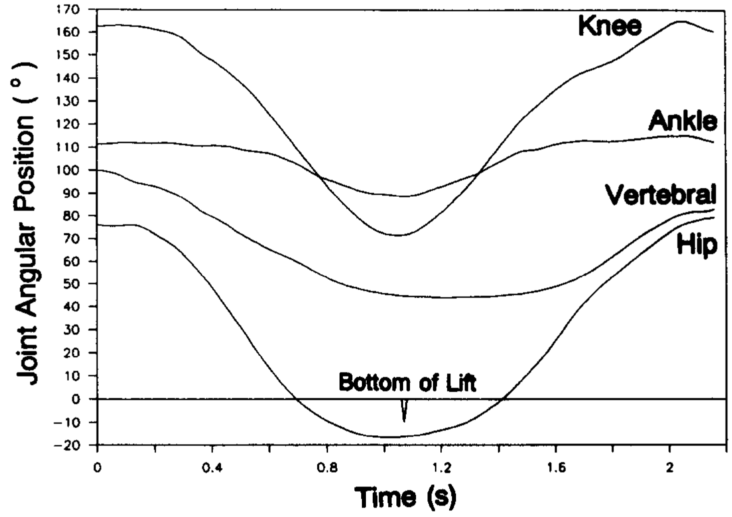

Fig. 1. Angular position of ankle, knee, hip and lumbar vertebral joints during a single lifting trial as a function of time. Points to the left of the bottom of the lift marker represent the subject's movements while flexing to pick up the load, while points to the right represent the loaded extension phase of the lift (Note: the data in this and all other figures are from the same trial, in which the load was 8.5 kg).

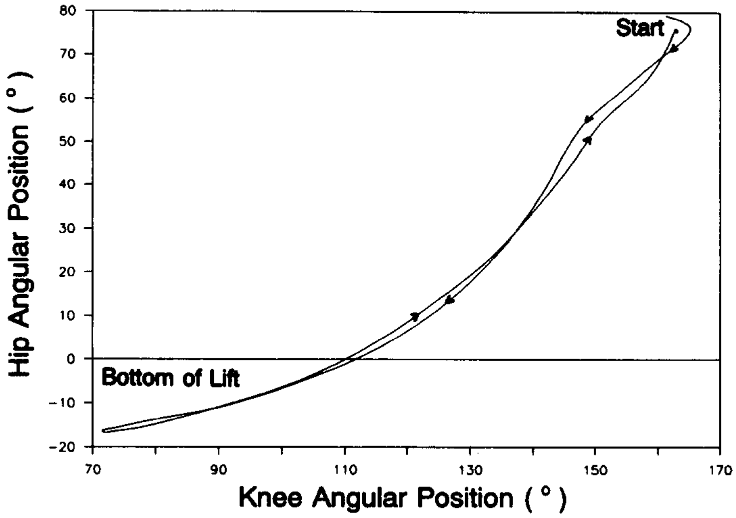

Fig. 2. Angular position of the hip plotted as a function of knee angular position during one lifting trial.

angular position. Such angle–angle presentations have been used to gain important qualitative information (e.g. Grieve, 1969; Soechting and Lacquanti, 1981; see Winstein and Garfinkel, 1989 for a discussion of qualitative dynamic techniques). The positive gradient of the angle–angle plot indicates that the interjoint coordination is in-phase, i.e. flexion occurs in both joints at the same time, followed by extension of both joints. If the interjoint coordination was perfectly synchronous then this angle–angle plot would be a straight line. The normal standing posture is represented at the top right corner. Flexion occurs rapidly at the hip which is then followed by the knee until full flexion is reached at the bottom left of the figure. Extension is the reverse, knee extension starting more rapidly than hip extension. Similar proximal–distal relationships exist at the ankle-knee and hip-vertebral complexes. While the deviation from synchronous in-phase coordination is qualitatively evident in this angle–angle presentation, quantification of the interjoint coordination is difficult.

Quantification can be achieved by using a phase plane analysis. Figure 3 is a plot of normalised knee angular velocity as a function of normalised knee angular position. The normalisation procedure scales the absolute maximum angular *velocity* to an absolute value of one, leaving points of zero angular velocity unaltered. Points of zero normalised angular velocity correspond to points at which the joint is momentarily stationary. The normalisation procedure sets the minimum and maximum angular *positions* to -1 and 1, respectively. A point of zero normalised angular position corresponds to the midpoint of the range of angular positions adopted by the joint during the movement of interest.

The lift starts on the right middle of the figure at maximum knee angular position and zero angular velocity and proceeds clockwise to minimum angular position and zero angular velocity at the mid-left side of the figure. Extension occupies the upper half of the figure. The position of the joint at any time during the movement can be defined in terms of an angular displacement from the starting point (at $t=0$) or

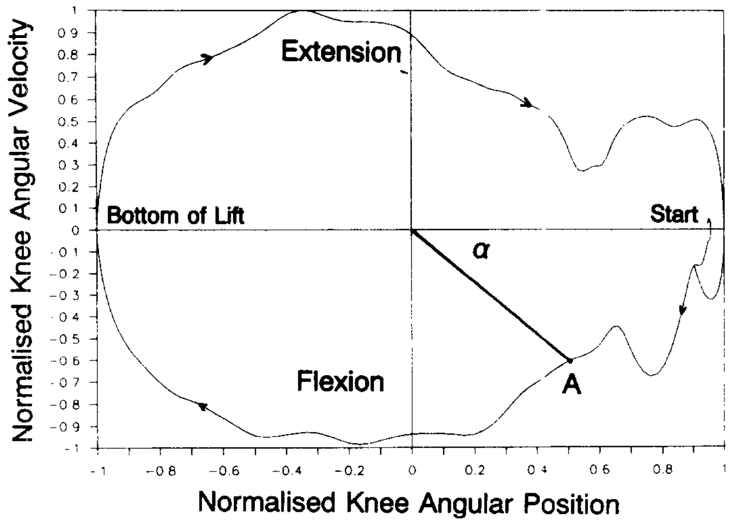

Fig. 3. Knee movement during one lifting trial plotted on the angular-velocity–angular-position phase plane.

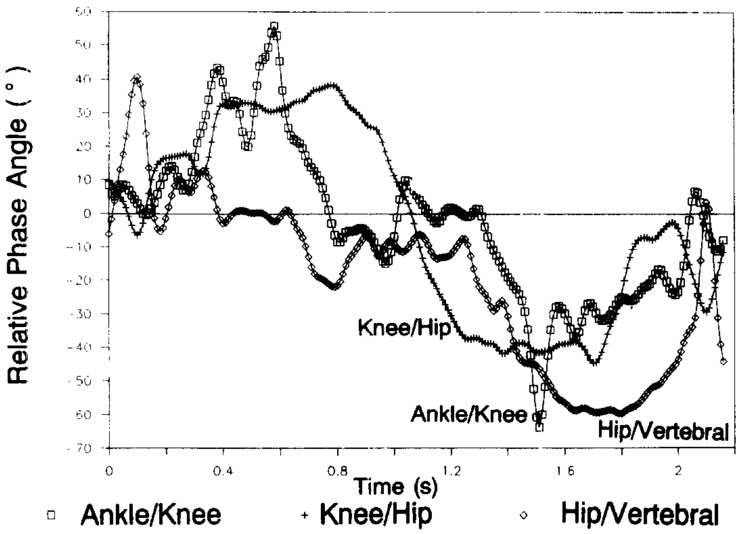

Fig. 4. The relationship between pairs of adjacent lower-limb joints in terms of relative phase angle as a function of time during one lifting trial.

phase angle (inverse tangent of normalised angular velocity/normalised angular position). For example, the position of the joint at point A is defined by the phase angle α (a positive clockwise convention was adopted).

The extent of the phase lag between two joints at any point in time (the deviation from perfect in-phase synchronisation) can be quantified as a relative phase angle by subtracting the phase angle of one joint from another (proximal–distal). The magnitude and temporal aspects of the proximal-to-distal coordination can be assessed through plotting relative phase as a function of time (Fig. 4). During the flexion phase of movement, the relative phase angles are positive, indicating that the proximal joints lead the distal joints, while in extension the relative phase angles are negative, quantifying the extent to which the proximal joints lag behind the distal during extension. Conventional statistical analysis may be used for relative phase angle data if the range of values is not large (i.e. $<90°$). Directional statistical techniques are appropriate when the range of values is large (see Batschelet, 1965; Burgess-Limerick, et al., 1991).

The use of angular position and velocity information to describe joint movement on a phase plane is advantageous on theoretical grounds because the afferent information available from muscle receptors is effectively in terms of joint position and velocity (McCloskey, 1978). The representation of movement on a phase plane may, thus, be meaningfully equated with the information available from the afferent receptors. The combination of phase angle information from two joints in a single relative phase angle measure allows quantative data about interjoint coordination to be gathered to supplement the qualitative information available from angular position vs time and angle–angle presentations. Relative phase angle may provide a measure which is sensitive to the effects of environmental changes, learning or other independent variables affecting movement coordination. An accurate description of multijoint coordination is an essential precursor to an understanding of the respective roles of monarticular and biarticular muscles, and the control of movement more generally.

Quantification of interjoint coordination through the use of the relative phase angle provides information that cannot be obtained through conventional angular position vs time presentation and may lead to substantive differences in interpretation of kinematic data. A strong argument can be made for the use of both types of analysis where interjoint coordination is relevant to the questions being addressed.

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