ELSEVIER
Human Movement Science 20 (2001) 549–562
HUMAN MOVEMENT SCIENCE
www.elsevier.com/locate/humov

Spontaneous transitions in the coordination of a whole body task

Robin Burgess-Limerick *, Jonathan Shemmell, Benjamin K. Barry, Richard G. Carson, Bruce Abernethy

School of Human Movement Studies, The University of Queensland, Brisbane, Qld 4072, Australia

Abstract

This paper describes an example of spontaneous transitions between qualitatively different coordination patterns during a cyclic lifting and lowering task. Eleven participants performed 12 trials of repetitive lifting and lowering in a ramp protocol in which the height of the lower shelf was raised or lowered 1 cm per cycle between 10 and 50 cm. Two distinct patterns of coordination were evident: a squat technique in which moderate range of hip, knee and ankle movement was utilised and ankle plantar-flexion occurred simultaneously with knee and hip extension; and a stoop technique in which the range of knee movement was reduced and knee and hip extension was accompanied by simultaneous ankle dorsi-flexion. Abrupt transitions from stoop to squat techniques were observed during descending trials, and from squat to stoop during ascending trials. Indications of hysteresis was observed in that transitions were more frequently observed during descending trials, and the average shelf height at the transition was 5 cm higher during ascending trials. The transitions may be a consequence of a trade-off between the biomechanical advantages of each technique and the influence of the lift height on this trade-off. © 2001 Elsevier Science B.V. All rights reserved.

PsycINFO classification: 2330

Keywords: Coordination; Spontaneous transitions; Lifting

* Corresponding author. Tel.: +61-7-3365-4718; fax: +61-7-3365-6877.
E-mail address: robin@hms.uq.edu.au (R. Burgess-Limerick).

0167-9457/01/$ - see front matter
PII: S0167-9457(01)00067-7

1. Introduction

Spontaneous transitions between different patterns of coordinated movement have the potential to provide important information about the role of neuromuscular constraints in the coordination and control of movement. Such transitions have been very well described and modeled in cyclic movements of peripheral limbs and limb segments (fingers, hands, feet, and arms). However, with the exception of gait transitions (Abernethy, Burgess-Limerick, Engstrom, Hanna, & Neal, 1995; Diedrich & Warren, 1995; Hanna, Abernethy, Neal, & Burgess-Limerick, 2000) whole body movements have not been similarly addressed. This research explores the boundaries of applicability of this approach by investigating the characteristics of spontaneous transitions in another whole body movement – one involving repetitive lifting and lowering of a load. Lifting and lowering is a particularly attractive task for study because of the amenability of the task constraints (height, mass, frequency) to independent manipulation and the relatively detailed biomechanical modeling of the movement which has been undertaken.

The first example of spontaneous transitions in human movement to be systematically examined was bimanual finger tapping (Kelso, 1981; Yaminishi, Kawato, & Suzuki, 1980). If a person is asked to tap both index fingers at a common frequency, but 180° out of phase (i.e., one finger reaches maximum flexion at the moment the other reaches maximum extension), this mode of coordination is stable and can be maintained accurately, at least at low tapping frequencies. If the frequency of finger tapping is gradually increased, the 180° mode can be maintained for some time. However at a critical value of the tapping frequency the coordination of the fingers suddenly (within one cycle) and spontaneously (unintentionally) changes so that flexion and extension of the two fingers occurs synchronously. In-phase coordination is now the only stable mode and this mode of coordination remains stable if the tapping frequency continues to increase (Kelso, 1984).

This phenomenon has been examined in some detail (e.g., Kelso, Scholz, & Schöner, 1986; Schöner & Kelso, 1988). If tapping frequency is decreased after the transition the system remains in the in-phase mode and no second transition occurs (i.e., the system exhibits hysteresis). If the system starts at low frequency in the in-phase mode, and then frequency is increased, no spontaneous transition occurs. The in-phase mode is more stable than the out-of-phase mode (indicated by lower variability). Intentional production of intermediate relative phase modes is difficult and the resulting coordination is much more variable than the in-phase or out-of-phase modes.

Similar observations have been made of transitions between patterns of intra-limb coordination. Kelso, Buchanan, and Wallace (1991) described spontaneous transitions between in-phase and out-of-phase coordination patterns of wrist and elbow flexion and extension as a function of frequency and whether the forearm was pronated or supinated. Buchanan and Kelso (1993) extended this observation, describing spontaneous transitions as a function of changes in forearm position while frequency remained constant.

This paper concerns an example of spontaneous transitions between different patterns of lower limb coordination as function of lift height during repetitive lifting and lowering. This example of spontaneous transitions in a whole body task provides an experimental paradigm which has potential to provide considerable insight into the role of musculoskeletal constraints in determining inter-joint coordination.

Manual lifting techniques are commonly differentiated on the basis of the posture adopted to lift a load. Distinctions are typically drawn between techniques involving a posture at the start of the lift in which the knee joints are flexed only slightly, if at all, and the trunk inclined substantially (a stooped posture), and a technique involving substantial knee flexion at the start of the lift and less trunk inclination (a squat or semi-squat posture) (e.g., Grieve, 1974; Kumar, 1984; Toussaint, van Baar, van Langen, de Looze, & van Dieën, 1992). Although the biomechanical consequences of different lifting techniques have been reported (e.g., Anderson & Chaffin, 1986; Gagnon & Smyth, 1992; Kumar, 1984; see Van Dieën, Hoozemans, & Toussaint, 1999, for a recent review), and an attempt has been made to define the different techniques quantitatively (Burgess-Limerick & Abernethy, 1997a), it is not known whether these different techniques represent qualitatively different modes of manual lifting, or points on a continuum. If the former were true then spontaneous transitions between different techniques might be anticipated in appropriate circumstances. In addition to providing a fruitful paradigm for investigating mechanisms of control and coordination, the observation of spontaneous transitions would also provide a justification for the previously assumed distinction in lifting techniques, and provide a more principled basis for subsequent biomechanical investigations.

Manual lifting, whether performed discretely or repetitively, involves cycles of flexion and extension movements of limbs and trunk. The pattern of self-selected, or preferred, lifting most frequently observed involves a semi-squat posture and simultaneous knee extension, hip extension and ankle plantar-flexion (Burgess-Limerick, Abernethy, Neal, & Kippers, 1995). Stooped postures were observed less frequently, and analysis of data from individual subjects gathered in previous experiments involving discrete lifting revealed some evidence for the existence of qualitatively different modes of discrete manual lifting (bi-modal distributions in parameters describing the postures adopted to lift loads; Burgess-Limerick & Abernethy, 1997a,b; see also Van Dieën, van der Burg, Raaijmakers, & Toussaint, 1988). An influence of starting height on the relative frequency of adoption of these modes was noted (stooped postures are more frequently adopted to lift loads from relatively high starting heights; Burgess-Limerick & Abernethy, 1997b; and semi-squat postures were almost always adopted to lift loads at floor height). However, transitions between different modes were not observed because, in these experiments, the lifting was either performed as discrete trials; or when repetitive lifting and lowering was examined, the experimental manipulations involved separate trials in different height conditions. The observation of transitions between different modes is impossible in the first case, and unlikely in the second. This paper describes an experimental paradigm in which such transitions were reliably observed and describes the fundamental characteristics of the phenomenon.

2. Method

Eleven participants (6 male, 5 female; aged 19–44 years) performed 12 trials of a task in which a 1 kg load was continuously raised and lowered. The lowest height of the load was indicated by a shelf connected to a computer controlled torque motor. The task involved repetitively lifting the load from this shelf to a constant height (waist level) then lowering the load back to the shelf. The height of the shelf was adjusted throughout each trial. A ramp protocol was employed for each trial such that the shelf was stepped once per cycle between 10 and 50 cm, in 40 equal steps. That is, each trial consisted of 40 cycles of lifting and lowering in which the shelf height varied continuously in 1 cm increments each cycle, either increasing from 10 to 50 cm (ascending trials) or decreasing from 50 to 10 cm (descending trials). The speed of lifting and lowering was self-selected by the participants. The changes in height of the of the lower shelf were manually timed to occur (within 0.25 seconds) during the midpoint of each ascending phase of lifting.

Participants first performed six trials in which the lifting technique was self-selected. The direction of the shelf movement on each trial alternated between ascending and descending. No instructions were provided regarding the lifting technique which should be employed. For the remaining six trials the participants were instructed to begin the trial in a specified technique and to continue to use this technique for as long as it is comfortable in a paradigm similar to the "do not intervene" instruction set introduced by Kelso (1984). The direction of shelf height change alternated between ascending and descending directions on successive trials. For the ascending trials the participants were instructed to begin the trial using a squat technique (involving significant knee flexion), while for the descending trials the participants were instructed to begin the trial using a stoop technique (involving minimal knee flexion). The angular displacement of ankle, knee, and hip, was recorded throughout all trials from three dimensional coordinates (100 Hz) of infrared emitting diodes (OPTOTRAK) placed on appropriate anatomical landmarks (see Burgess-Limerick, Abernethy, & Neal, 1993; Burgess-Limerick et al., 1995; for definitions). Complete data were available for 121 of the 132 trials performed.

Two qualitatively different patterns of coordination were exhibited: a squat technique and a stoop technique. The squat technique is characterised by a moderate range of motion at ankle, knee, and hip joints, and in phase coordination (simultaneous ankle plantar-flexion, knee extension, and hip extension). The stoop technique is described as a pattern of coordination in which the range of movement of the knee was reduced and the coordination of the ankle was 180° out of phase with respect to the other joints (i.e., ankle plantar-flexion was accompanied by knee flexion and hip flexion).

The presence of abrupt transitions between techniques, and the height at which transitions occurred was determined by calculating the continuous relative phase between the ankle and the knee, and the ankle and the hip, using a Matlab routine based on the Hilbert transform. Approximate transition points were first identified by simultaneously viewing continuous relative phase data and angular displacement data for the ankle, knee and hip. Custom computer software, incorporating an interactive visual display, was then utilised to identify an exact transition time. Approximate transition points were identified with two markers placed in a region prior to a transition, and two markers placed in a region following a transition. Within these pre- and post-transition regions the mean relative phase value was calculated and a mid-mean value was taken as the median between these two. The transition region was searched for a relative phase angle corresponding to the median, and a linear regression was calculated about this point. The start and end points of the transition were defined as the points at which the regression function intersected with the pre- and post-transition means. The point of transition was the height of the shelf corresponding to the transition start time.

Chi square was calculated to assess whether the frequency of transitions was related to the direction of the trials (ascending or descending). For those participants who exhibited transitions in both ascending and descending trials, the average shelf heights at which transitions occurred used to estimate the magnitude of the hysteresis effect using Cohen's effect size (d) and submitted to one-way analysis of variance.

3. Results

Two qualitatively different patterns of coordination were spontaneously adopted when the lifting technique was self-selected: a squat technique and a stoop technique. The squat technique is characterised by a moderate range of motion at ankle, knee, and hip joints, and in phase coordination (simultaneous ankle plantar-flexion, knee extension and hip extension). This pattern of coordination is illustrated in Fig. 1(a) in an ascending trial in which the pattern of coordination was maintained throughout the complete range of shelf heights. This is a very consistent pattern of coordination which was adopted by all participants. The stoop technique is broadly described as a pattern of coordination in which the range of movement of the knee was reduced and the coordination of the ankle was 180° out-of-phase with respect to the other joints (ie., ankle plantar-flexion was accompanied by knee flexion and hip flexion). A typical stoop technique is illustrated in Fig. 1(b) in a descending trial in which the technique was maintained for the complete range of shelf heights. Seven of the 11 participants adopted both stoop and squat patterns during the six self-selected trials, while the remaining four adopted the squat pattern for all self-selected trials.

Abrupt transitions between techniques were demonstrated by nine of the 11 participants, in 55% of the total number of trials (66 of 121 trials). The remaining two participants adopted a squat pattern for all self-selected trials and remained in the initial technique throughout the imposed trials. Transitions from squat (in-phase) to stoop (out-of-phase) coordination occurred during ascending trials, and transitions from stoop to squat patterns occurred during descending trials, in both self-selected and imposed trials. Fig. 2 illustrates examples of both transition directions.

Some variability existed in the nature of the inter-joint coordination during the stoop technique, and the characteristics of the transitions observed. For

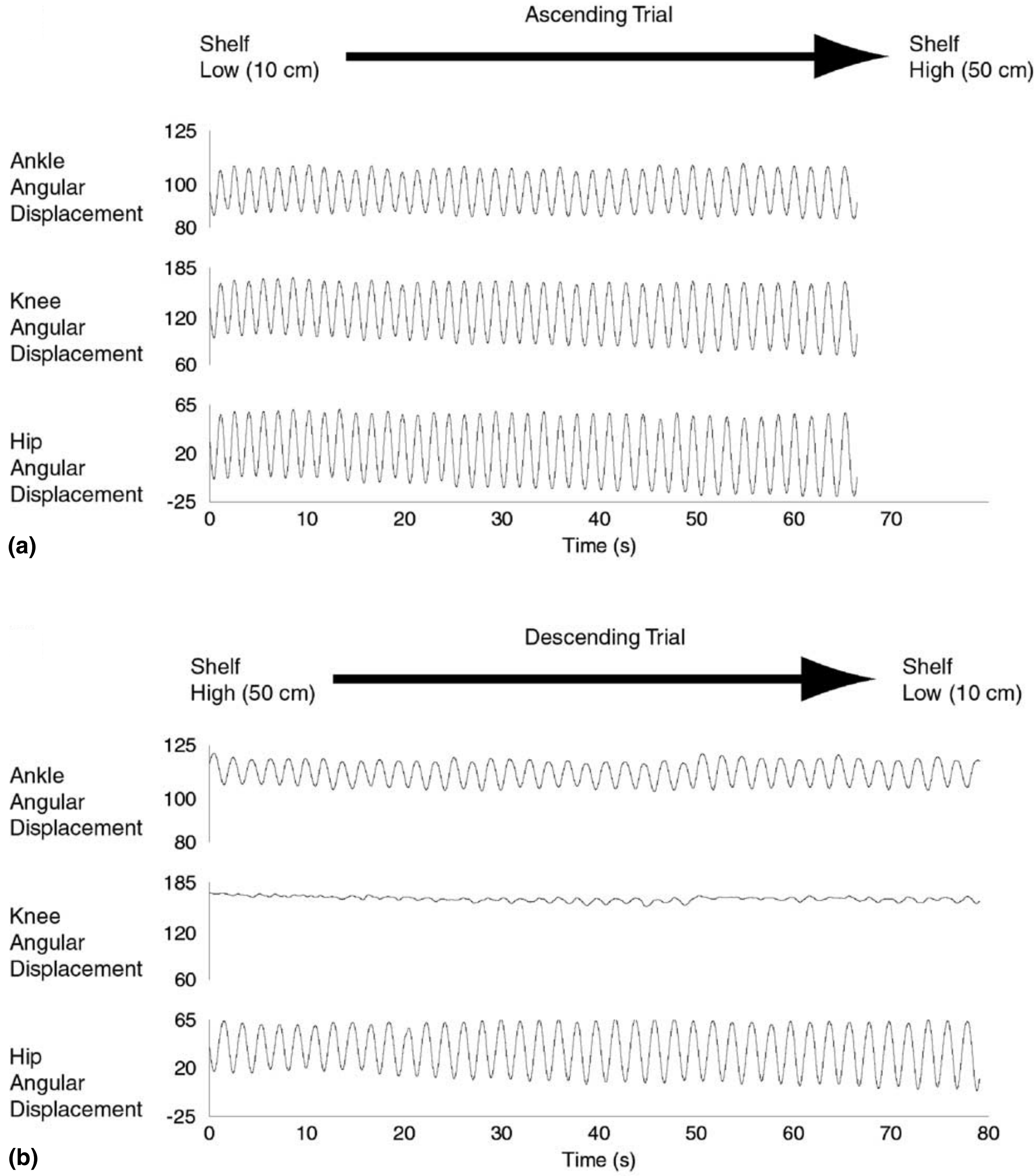

Fig. 1. Two trials of cyclic lifting and lowering in which continuous changes in lower shelf height did not induce transitions between qualitatively different patterns of coordination. (a) Illustrates an ascending trial in which the shelf height was initially 10 cm, and increased to 50 cm over 40 cycles. A squat pattern of coordination was self-selected, involving in-phase coordination of the ankle, knee and hip joints. The bottom case illustrates a descending trial in which the shelf height was decreased from 50 cm to 10 cm over 40 cycles. A stoop pattern of coordination was adopted, involving anti-phase coordination of the ankle and a reduction of movement about the knee joint.

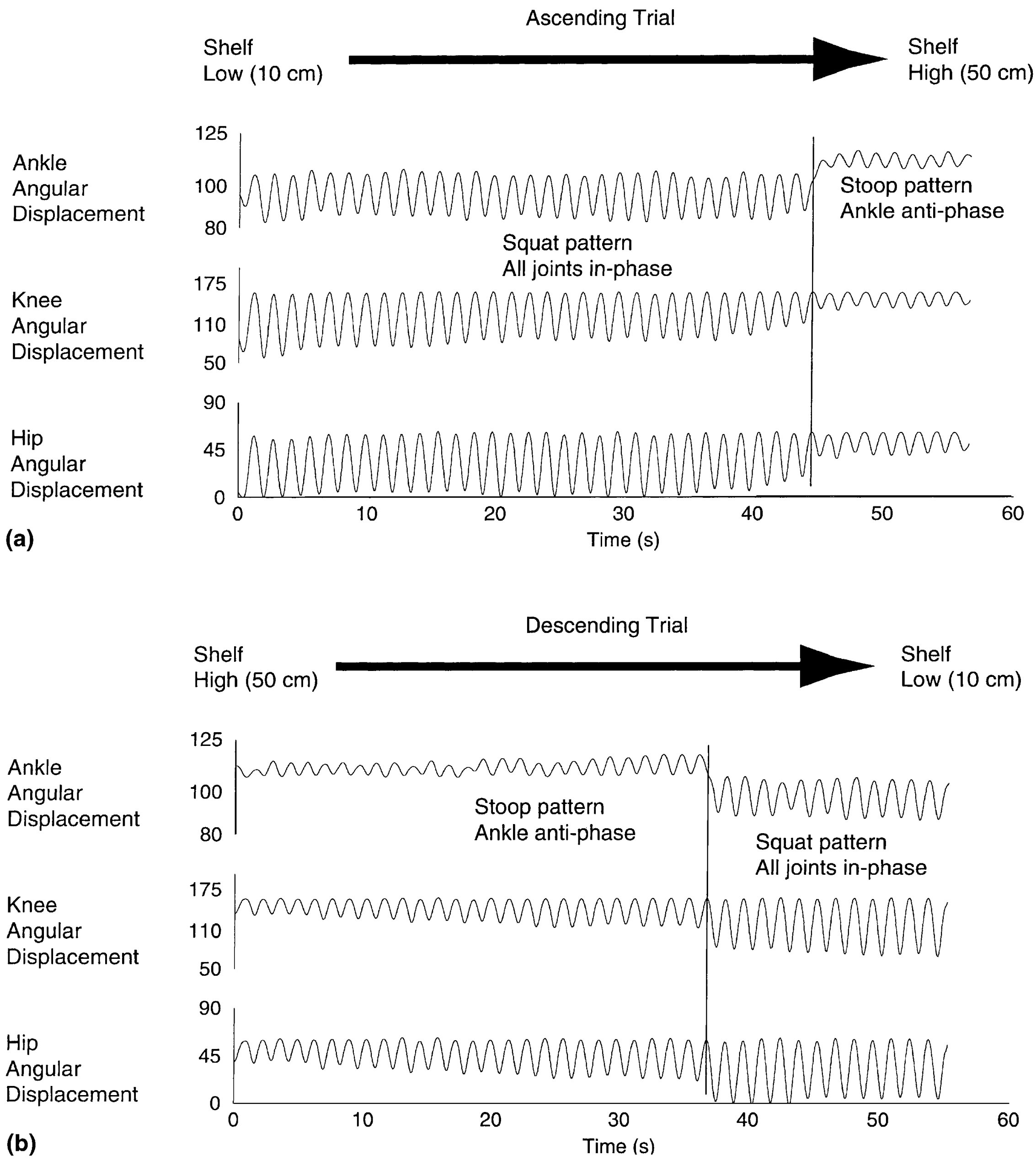

Fig. 2. Spontaneous transitions occurred between the stoop and squat lifts during both the ascending and descending trials. In the ascending trial (a) a squat pattern of coordination was maintained for 32 cycles (until the shelf height was 42 cm) when a transition to the stoop pattern occurred. In the descending trial (b) a stoop pattern of coordination was maintained for 28 cycles (until the shelf height was 22 cm).

example, the range of motion at the knee during the stoop pattern varied between participants. In contrast to the participant illustrated in Fig. 2, the participant illustrated in Fig. 3 demonstrated a stoop technique involving almost no knee movement. Variability also exhibited in the characteristics of

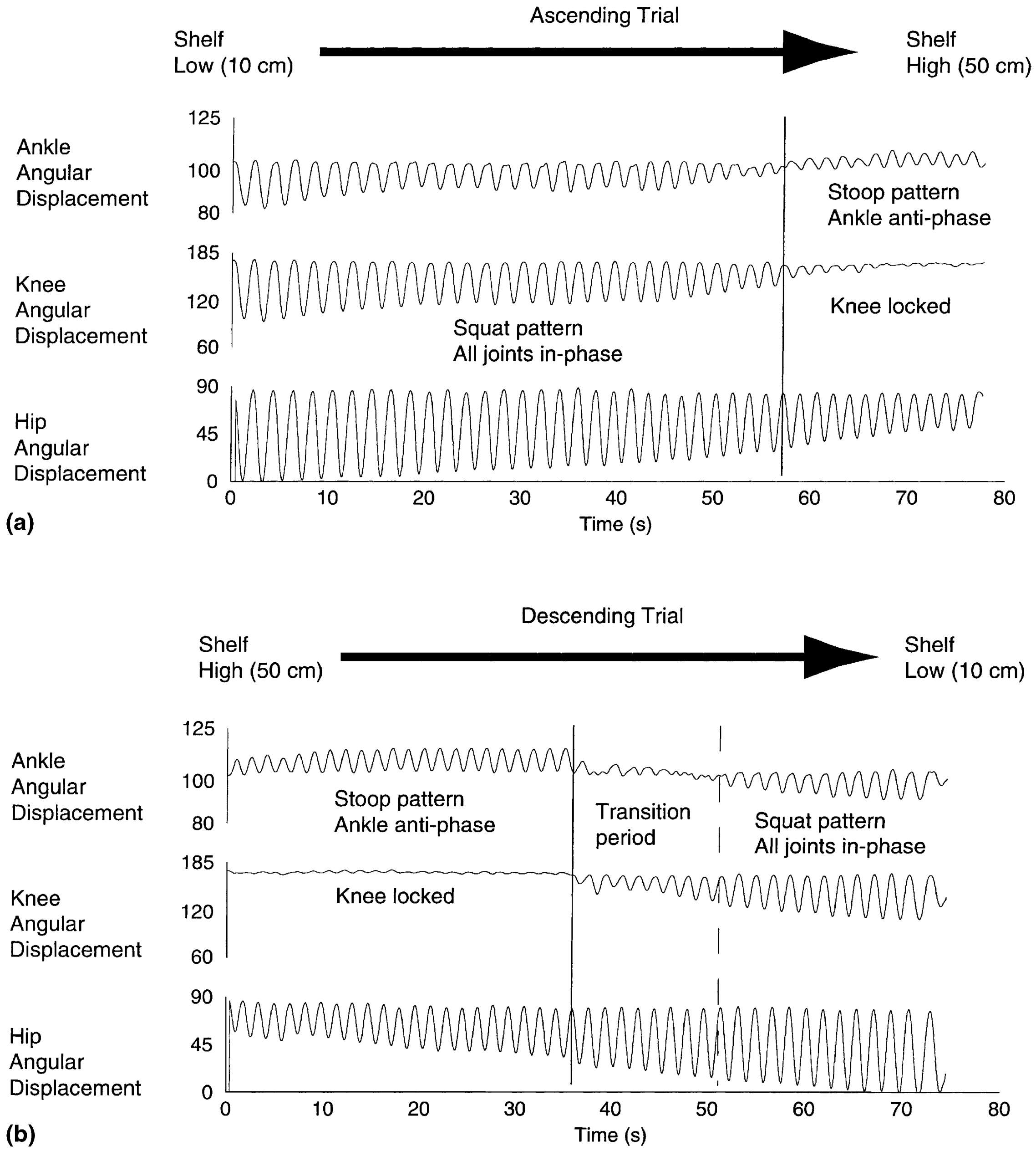

Fig. 3. Spontaneous transitions between qualitatively different patterns of coordination are exhibited in both the ascending and descending trials. In the ascending trial (a) a squat pattern of coordination was maintained for 31 cycles (until the shelf height was 41cm) when a transition to the stoop pattern occurred. In the descending trial (b) a stoop pattern of coordination was maintained for 22 cycles (until the shelf height was 28 cm).

the transitions observed. Whilst the transition from squat to stoop in the ascending trial illustrated in Fig. 3(a) is abrupt, a transition period between techniques was sometimes observed in the transition from stoop to squat

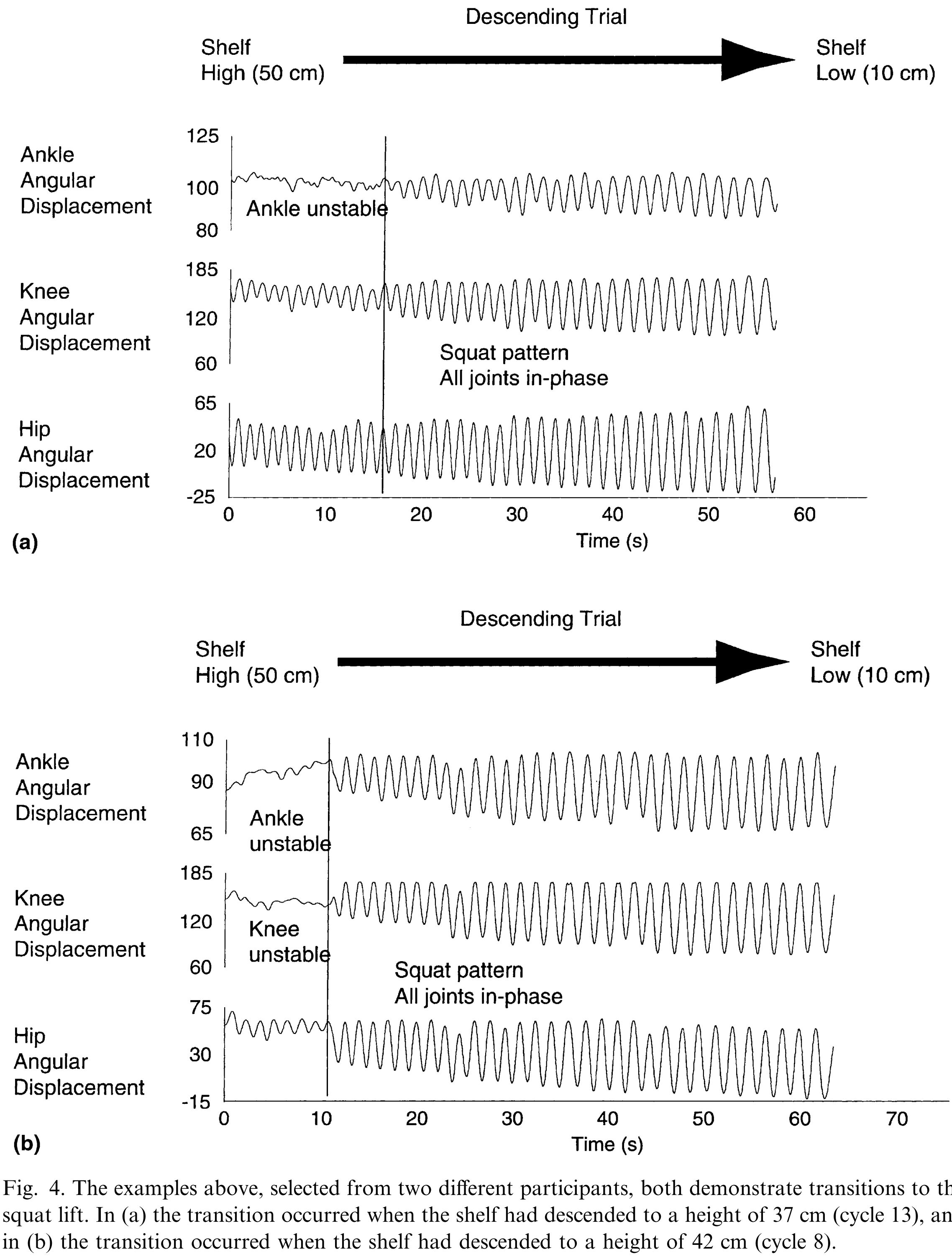

Fig. 4. The examples above, selected from two different participants, both demonstrate transitions to the squat lift. In (a) the transition occurred when the shelf had descended to a height of 37 cm (cycle 13), and in (b) the transition occurred when the shelf had descended to a height of 42 cm (cycle 8).

such as that illustrated in the descending trial presented in Fig. 3(b). There were also some participants (see Fig. 4 for examples) who adopted unstable patterns of ankle and knee movement when asked to adopt a stoop technique, before abruptly changing to a squat pattern as shelf height decreased.

Indications of hysteresis were observed in that transitions occurred more frequently during descending trials than during ascending trials ($\chi^2 = 6.51$, $p < 0.05$); and for those six participants who exhibited transitions in both directions, the average shelf height at which the transition occurred was 5 cm higher in the ascending trials than in the descending trials (36 vs 31 cm, $d = 0.79$ (95% confidence interval −0.3 to 1.8), $F[1, 5] = 3.81$, $p = 0.11$).

4. Discussion

The observation of abrupt transitions between qualitatively different patterns of manual lifting provides a justification for the distinction which has traditionally been made between squat and stoop methods of lifting. Further, the identification of the change in phase relationships between the ankle and hip provides a means of solving the problem of how to define the techniques independent of the absolute range of motion of the knee (see Burgess-Limerick & Abernethy, 1997a).

The observation that both patterns of coordination were adopted and maintained throughout the complete range of shelf heights involved (10 to 50 cm), and that participants could adopt both patterns when instructed to do so, suggests that the neuromuscular constraints which contribute to the coordination of the movement allow multiple patterns of coordination to be adopted. The technique adopted to perform the task is influenced systematically by the height of the shelf from which the load is to be lifted. As previously noted (Burgess-Limerick & Abernethy, 1997b), a stoop technique is more likely to be adopted when the shelf height is relatively high and, in this experiment, abrupt transition from stoop to squat technique were observed when the shelf height was gradually lowered. Although somewhat less frequent, abrupt transitions also occurred from squat to stoop technique when the shelf height was gradually raised. These observations beg the question of what are the biomechanical consequences of the different techniques, how are these modified by changes in the shelf height, and what variable or combination of variables correspond to the changes in movement coordination. It seems likely that the coordination is determined by balancing a coalition of constraints which vary somewhat between individuals, perhaps as a function of anthropometric variability, and with changes in task constraints.

It has been noted that adopting a squat posture involving moderate flexion at hip and knees has the advantage of allowing a functional distal-to-proximal pattern of inter-joint coordination to be adopted (Burgess-Limerick et al., 1995). Whilst knee, hip and lumbar vertebral extension occurs contemporaneously, the coordination deviates systematically from perfectly in phase. Lifting from a semi-squat posture commences with rapid knee extension, followed by extension of the hip, and significant lumbar vertebral extension is delayed substantially after the start of the lift. Estimation of the length changes of the biarticular hamstring muscles revealed that the coordination between knee and hip joints has the consequence of delaying rapid shortening of the hamstrings. Similarly, the delay before rapid lumbar vertebral extension delays rapid shortening of the erector spinae.

Muscles are stronger when not shortening rapidly and thus the pattern of coordination involved in lifting from a posture involving moderate knee flexion increases the strength of the hamstrings and erector spinae early in the extension phase when the acceleration of the load is greatest. Delaying shortening of the hamstrings has the additional functional consequence (supported by electromyographic data) of allowing the monoarticular knee extensors to, paradoxically, contribute to *hip* extension through a tendinous action of the hamstrings (cf. de Looze, Toussaint, van Dieën, & Kemper, 1993; Toussaint et al., 1992). The pattern of coordination is made possible by the adoption of a posture involving a moderate range of knee flexion at the start of the lift, and reduces the muscular effort required to perform the task by utilising the physical characteristics of the neuromuscular system. Further, this pattern of inter-joint coordination, and the consequences for delayed rapid muscle shortening, have been previously shown to be exaggerated by increases in load mass (Burgess-Limerick et al., 1995).

A different pattern of coordination occurs when stooped postures are adopted at the start of extension. The large range of hip flexion and small range of knee flexion (or even slight extension) means that the biarticular hamstrings are lengthened further (and are thus stronger isometrically) than if a semi-squat posture were adopted. A stooped posture also has the advantage of lowering the centre of gravity less than a semi-squat and thus less mechanical work is done to lift the body during each lift (Kumar, 1984). However, during lifting the hamstrings must immediately shorten rapidly because the knee is unable to extend rapidly. This counteracts to some extent the strength advantage which accrues as a consequence of the increased hamstring length. Rapid shortening of the hamstrings also prevents the monoarticular quadriceps from contributing to hip extension.

This trade-off between the costs and benefits of different movement patterns, and the influence of other constraints such as initial load height and lifting speed on the trade-off, is likely to be the source of the transitions observed. It seems likely that, for some people at least, when the lift speed is self-selected the balance of advantage between these techniques is altered sufficiently by the change in shelf height to induce an abrupt change in the pattern of coordination. The question remains – what variable, or combination of variables, is the lifter sensitive to, and how does this coalition of constraints influence the pattern of coordination adopted?

References

Abernethy, B., Burgess-Limerick, R., Engstrom, C., Hanna, A., & Neal, R. J. (1995). Temporal coordination of human gait. In J. Piek (Ed.), *Motor control and sensory motor integration* (pp. 171–196). Amsterdam: Elsevier.

Anderson, C. K., & Chaffin, D. B. (1986). A biomechanical evaluation of five lifting techniques. *Applied Ergonomics*, *17*, 2–8.

Buchanan, J. J., & Kelso, J. A. S. (1993). Posturally induced transitions in rhythmic multijoint limb movements. *Experimental Brain Research*, *94*, 131–142.

Burgess-Limerick, R., & Abernethy, B. (1997a). Towards a definition of manual lifting technique. *Human Factors*, *39*, 141–148.

Burgess-Limerick, R., & Abernethy, B. (1997b). Qualitatively different modes of manual lifting. *International Journal of Industrial Ergonomics*, *19*, 413–417.

Burgess-Limerick, R., Abernethy, B., & Neal, R. J. (1993). Technical note: Relative phase quantifies interjoint coordination. *Journal of Biomechanics*, *26*, 91–94.

Burgess-Limerick, R., Abernethy, B., Neal, R. J., & Kippers, V. (1995). Self-selected manual lifting technique: Functional consequences of interjoint coordination. *Human Factors*, *37*, 395–411.

de Looze, M. P., Toussaint, H. M., van Dieën, J. H., & Kemper, H. C. G. (1993). Joint moments and muscle activity in the lower extremities and lower back in lifting and lowering tasks. *Journal of Biomechanics*, *29*, 1067–1076.

Diedrich, F. J., & Warren, Jr. W. H. (1995). Why change gaits? Dynamics of the walk run transition. *Journal of Experimental Psychology, 21*, 183–202.

Gagnon, M., & Smyth, G. (1992). Biomechanical exploration on dynamic modes of lifting. *Ergonomics*, *35*, 329–345.

Grieve, D. W. (1974). Dynamic characteristics of man during crouch- and stoop-lifting. In R. C. Nelson, & C. A. Morehouse (Eds.), *Biomechanics* (IV) (pp. 19–29). Baltimore, MD: University Park Press.

Hanna, A., Abernethy, B., Neal, R. J., & Burgess-Limerick, R. (2000). Triggers for human gait transitions. In W. A. Sparrow (Ed.), *Metabolic energy expenditure and the learning and control of movement* (pp. 124–164). Champaign, Il: Human Kinetics.

Kelso, J. A. S. (1981). Contrasting perspectives on order and regulation in movement. In J. Long, & A. Baddeley (Eds.), *Attention and performance IX* (pp. 437–457). Hillsdale, NJ: Erlbaum.

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology*, *246*, R1000–R1004.

Kelso, J. A. S., Buchanan, J. J., & Wallace, S. A. (1991). Order parameters for the neural organization of single multijoint limb movement patterns. *Experimental Brain Research*, *85*, 432–444.

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: Critical fluctuations. *Physics Letters A*, *118*, 279–284.

Kumar, S. (1984). The physiological cost of three different methods of lifting in sagittal and lateral planes. *Ergonomics*, *27*, 425–433.

Schöner, G., & Kelso, J. A. S. (1988). Dynamic patterns of biological coordination: Theoretical strategy and new results. In J. A. S. Kelso, A. J. Mandell, & M. F. Shlesinger (Eds.), *Dynamic patterns in complex systems* (pp. 77–102). Singapore: World Scientific.

Toussaint, H. M., van Baar, C. E., van Langen, P. P., de Looze, M. P., & van Dieën, J. H. (1992). Coordination of the leg muscles in leglift and backlift. *Journal of Biomechanics*, *25*, 1279–1289.

Van Dieën, J. H., Hoozemans, M. J. M., & Toussaint, H. M. (1999). Stoop or squat: A review of biomechanical studies on lifting technique. *Clinical Biomechanics*, *14*, 685–696.

Van Dieën, J. H., van der Burg, P., Raaijmakers, T. A. J., & Toussaint, H. M. (1988). Effects of repetitive lifting on kinematics: Inadequate anticipatory control or adaptive changes? *Journal of Motor Behavior*, *30*, 20–32.

Yaminishi, J., Kawato, M., & Suzuki, R. (1980). Two coupled oscillators as a model for the coordinated finger tapping by both hands. *Biological Cybernetics*, *37*, 219–225.