Reflections on physiotherapy and the emerging science of movement rehabilitation

Recent scientific advances in the field of human movement and its control have provided the impetus for developing new ways of thinking about the training and measurement of motor performance in individuals with movement dysfunction and are challenging traditional methods of practice. In this paper, the authors describe the process of importing knowledge from established fields of science to develop a more scientific framework for clinical practice. In addition, they present some of the results of their laboratory-based research into the control of the upper body and lower limbs in sit-to-stand and illustrate the process by which they have developed a protocol for optimising performance of sit-to-stand in training disabled individuals.


Key words: Biomechanics; Physical Therapy; Rehabilitation

The primary goal of rehabilitation in individuals with movement dysfunction associated with lesions of the neuromuscular system is the optimising of functional motor performance. Physiotherapists play a major role in training such individuals to gain the necessary muscle strength and control over body segments, so enabling the achievement of optimal motor performance.

Physiotherapy and movement rehabilitation are currently in a period of major change (Shepherd and Carr 1994). The impact of recent scientific advances in the field of human movement and its control have provided the impetus for developing new ways of thinking about the training and measurement of motor performance in individuals with movement dysfunction. New insights into human movement are providing new theoretical perspectives for rehabilitation as well as challenging traditional methods of practice.

The importation of knowledge from established fields of science is said to be a typical early stage in the development of any scientific field (Abernethy and Swallow 1992, Kuhn 1970). Since the last decade, well-tested theoretical concepts and data from the areas of science related to human movement are being imported into neurological physiotherapy as a means of developing physiotherapy from a praxis- or person-orientation to a more scientifically-based clinical practice (Carr and Shepherd 1982, 1987a, 1987b, 1989 and 1991). In the authors' collaborative work and in the work of others, eg Ada and Canning (1990), Ada et al (1994), Engardt et al (1992 and 1993), Malouin et al (1992), Richards et al (1991) and Taub et al (1993), theories and data from such fields as neuroscience, biomechanics, cognitive and environmental psychology, motor learning and muscle biology are being utilised to develop a more scientific framework for clinical practice.

They have collaborated since 1980 on development of a model for rehabilitation of movement disabled individuals based on research findings related to human motor performance. They have co-authored three textbooks and co-edited a book on the relationship between movement science and rehabilitation, all of which have been translated into several languages. Currently, Associate Professor Carr is the President of the Australian College of Physiotherapists and Professor Shepherd is the College's Chief Censor.

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This importation from relevant fields outside physiotherapy in turn fosters an attitude of hypothesis-testing, which is part of the nature of science. In addition, where basic scientific knowledge is lacking, physiotherapists, often collaborating with scientists in other fields, are carrying out research designed to provide answers to questions relevant to the clinic and, in some cases, to explore questions related to the very nature of human movement itself, eg Carr and Gentile (1994), Gordon et al (1990), Kilbreath and Gandevia (1993) Sahrmann and Norton (1977), Shepherd and Gentile (1994) and Woollacott et al (1986).

The authors' participation in this process of change started early in the last decade with the publication of an undergraduate text (Carr and Shepherd 1980). In this work, the notion was introduced that research findings and theoretical perspectives in the field of motor learning were relevant to clinical practice. An attempt was made to give examples of how this knowledge could be utilised in clinical practice. This was followed in 1987 by two other texts and a congress paper (Carr and Shepherd 1987a and 1987b, Shepherd 1987) in which it was proposed that clinical physiotherapy be based on theoretical perspectives and data-based findings in the broad area of human movement science. Neuroscience, biomechanics, cognitive and ecological psychology, and muscle biology were added to motor learning as relevant fields of study. The authors' clinical publications have, therefore, largely been related to illustrating for clinicians how scientific findings from fields outside physiotherapy can be imported into the field and are fruitful sources of information necessary to the development and testing of clinical interventions. The strategy has been to demonstrate both the way in which clinical implications can be derived from research findings and how this information can be used to generate testable hypotheses. The authors have stressed the need to measure outcome, in particular the effect of training on functional motor performance (Carr et al 1985), since functional performance is the desired outcome.

The authors' scholarly interest over the past 15 years has been in the development of a theoretical framework for rehabilitation. This work has involved in part the integration of information from the literature and in part the collection of data on the control of the multisegmental linkage in the performance of natural tasks. Studies of the ways in which able-bodied subjects acquire skill in movement have provided information pertinent to the motor training of disabled individuals who must again acquire skill in performance. There is now a considerable body of knowledge on such relevant issues as practice, the use of feedback, motivation and the importance of attending to the appropriate environmental cues. Studies of muscle, joint movement and multisegment action have increased understanding of the need for practice to be specific to both task requirements and contextual variability. The field of biomechanics has been a particularly fruitful source of new knowledge, since it provides information about the nature and mechanics of normal and disabled motor performance. Such information has enabled the preliminary development of protocols for training more effective performance and provided insights into motor control and dyscontrol processes.

In current laboratory work, the authors are examining the control of the lower limbs in natural actions which involve the rotation of linked segments about a fixed base of support, eg sit-to-stand, squat-to-stand and reaching in sitting. The lower limbs play a critical role in support, balance and propulsion. This role can be exemplified in the action of sit-to-stand, in which the lower limbs act to propel the body mass from the seat to the standing position, to support and balance the body mass over the feet. In this experimental work, hypotheses related to the control and regulation of a dynamic system are being tested.

Sit-to-stand is a useful model for laboratory investigation of the control of multisegment movement. The environmental features which usually constrain the action, that is, the seat and the floor, can be provided in a laboratory and the action can, therefore, be performed relatively naturally. The action is relatively symmetrical and performed predominantly in the sagittal plane, so can be studied in two dimensions.

The laboratory-based research has taken three cooperative directions. In one, sit-to-stand has been used as a model for describing the action itself under different conditions as well as investigating the control of linked segments as they move over a fixed base of support. With colleagues, this work includes studies of the contribution of the arms to balance and propulsion (Carr and Gentile 1994) and of the dynamic intersegmental relationships between trunk and lower limb segments (Shepherd and Gentile 1994). In addition, the effects of different foot placements (Rajaratnam and Shepherd 1994, Shepherd and Koh, 1993) and of speed of movement (Carr and Ow, 1994) on biomechanical features of sit-to-stand in able-bodied subjects have been examined. The action of the lower limbs during squat-to-stand, and stepping up and down currently are being examined to test certain hypotheses related to lower limb control.

The second research direction involves identifying the changes taking place during motor development and the dyscontrol characteristics associated with various lesions such as stroke, diplegic cerebral palsy and following hip replacement. A third stream of research is the testing of hypotheses related to the training of sit-to-stand in the clinic. In these studies, hypotheses concerning the effects of auditory or visual feedback and of modifying seat height to potentiate performance in individuals following stroke are being examined.

The authors set out to relate the findings of their studies, and those of others, in developing a normal model
of sit-to-stand as a guide to evaluation and training of this action in the clinic. Standing up is a significant action in clinical practice, since it is one of the most common everyday activities and essential for independence. It is a pre-requisite for locomotion in the sense that it must be possible to get out of a chair in order to be able to walk off. Standing up is one of the most mechanically demanding of daily actions (Berger et al 1988) and lack of independence in standing up is reported to be one of the likely factors associated with risk of institutionalisation (Branch and Meyers 1987).

Dynamics of sit-to-stand

This section describes some of the results of the authors' laboratory research and illustrates the process by which they have developed a protocol, based on a scientific framework, for optimising sit-to-stand performance in individuals with disability. First, a brief description is given of the methodology used in these studies. The development of a consistent methodology has enabled some comparisons across studies but more importantly, has made it possible to ensure that differences in biomechanical parameters can be attributed to the different experimental conditions and are not merely the result of changes in, for example, the subject's starting position. Second, some findings of interest are outlined and indications given of the clinical implications arising from the data which can be utilised in the training of disabled individuals.

Methodology

In most of the studies reported in the next section, subjects were selected to form relatively homogeneous groups. When the study called for able-bodied subjects, subjects were chosen if they had no known musculoskeletal or neurological dysfunction.

Apparatus and procedure

Subjects sit on a height-adjustable seat (comprising a flat sitting surface and without arms) with their ischial tuberosities positioned directly over a pressure-sensitive switch strapped on to the front of the seat. Approximately one third of the thighs is, therefore, supported by the seat. The switch is connected both to a light in view of a video camera, and to a computer which samples forceplate signals. Deactivation of the light and opening of the switch signals a loss of contact with the seat, the event called thighs-off.

Light-reflecting markers are placed on the subject’s skin on one side of the body over anatomical landmarks, for example, the lateral aspect of the glenohumeral joint, greater trochanter, knee joint, lateral malleolus, heel and foot (Figure 1). It should be noted that, for the purpose of analysis, the arms, head and trunk are included in the trunk segment. The markers define a rigid four-segment model, made up of trunk, thigh, shank and foot (Figure 1).

![Figure 1](image)

**Figure 1**

The 4-segment model used in kinematic analyses showing absolute or segment angles. Key: str = trunk (hip); th = thigh (knee); sh = shank (ankle).

In early studies of sit-to-stand, Fourier analysis indicated that there is no significant information in frequency components above 2Hz in able-bodied subjects, so data is typically filtered with 2Hz as the cut-off. In disabled subjects, however, and under certain conditions, the cut-off may extend up to 3 or 4Hz.

In studies in which subjects stand up under different conditions, the order in which each subject performs the conditions is randomised. Subjects are instructed to stand up at their normal preferred speed, described to them as a natural comfortable speed. Previous data has indicated that when speed was defined in this way, 94.5 per cent of all trials fell within 1.5 SD of the mean total movement time. Any trials that do not meet this criterion are usually eliminated at the data analysis stage.

Standardisation

The subject's starting position is standardised in terms of seat height and initial segmental alignment. Developing a standardised starting position has enabled some comparisons across studies. In studies which involve able-bodied subjects, standardisation has enabled testing of the effects of experimental manipulations of, for example, initial foot position.
The results of the following studies of the laboratory, coordinate data (X,Y) are manually digitised. The digitising procedure is controlled by a computer software package (Smith 1987) which is designed to analyse human movement. The analysis involves filtering the input coordinate data using a low-pass, critically-damped digital filter (4th order, Butterworth-type). The software package is used to determine segmental and total body kinematics and kinetics, for example joint moments of force, as well as support moment of force as described by Winter for stance phase of walking (1980). The latter is calculated as an algebraic summation of the moments about the hip, knee and ankle is, therefore, a useful measure of the extensor force generated throughout the limb. Kinetic data are normalised by dividing the moment of force and power by each subject's body mass. As shown in Figure 1, segment angles are calculated as absolute angles in space in a four-segment three-joint system. For ease of description throughout the next section, however, instead of trunk, thigh and shank, the terms hip, knee and ankle may be used to represent the joints at which the segments rotate.

Three events provide reference points: movement onset, thighs-off and movement end. Movement onset is usually defined in terms of linear shoulder marker movement. The second event, thighs-off, is the time at which contact with the seat-switch is broken. The third event, movement end, is defined in terms of linear movement of the hip marker. These events enable the action to be divided into two phases, a pre-extension and an extension phase.

**Research findings and their implications**

The results of the following studies of sit-to-stand performed in the laboratory provide some insight into the nature of the control of the lower limbs in support, balance and vertical propulsion of the body mass and illustrate both the consistency and the flexibility inherent in the performance of this multisegment action. They also provide implications of interest to clinical practice.

**The contribution of upper body to lower limb extension**

Several studies have pointed to the importance of forward rotation of the trunk segment in setting up the conditions for ascent into standing. The results of two studies (Canning et al 1985, Schenkman et al 1990) have suggested that a timing relationship between trunk flexion and lower limb extension may be a critical feature in the movement's organisation. Peak acceleration of the flexing trunk segment has been found to occur simultaneously with the onset of lower limb extension at the knee (Canning et al 1985). Schenkman and colleagues (1990) have proposed that forward momentum of the trunk may facilitate the lower limb extension action which raises the body to the standing position. Recently, Pai and Rogers (1990 and 1991) have shown that the trunk is a major contributor to horizontal linear momentum of the centre of body mass, with the thigh segment being the major contributor to vertical momentum.

Shepherd and Gentile (1994) investigated the relationship between the trunk and the lower limb segments by varying the initial position of the trunk segment. Subjects stood up from three different starting positions: trunk erect (ES), trunk flexed 30 degrees (TF), and trunk flexed 60 degrees (TFF) (Figure 2).

Support moment (SM) was examined as a global measure of the function of the lower limbs in support and propulsion. The peak value of support moment remained consistent across conditions (mean= 4.7 N.m/kg SD= 0.5) despite variability in the forces produced over the three joints. It was evident that forces at individual joints varied in a cooperative manner to produce the overall force necessary to propel the body mass vertically, with a decrease in force at one joint being compensated for by an increase at the other joints. These findings, together with those of Winter (1987) for the stance phase of walking, suggest support moment provides a link between actions which require the lower limbs to be functionally stiffened in order both to resist collapse and to bring about vertical propulsion of the body mass.

The results indicated that a high level of support moment had to be sustained over a longer period of time when subjects stood up from the fully flexed position of the trunk, ie when subjects stood up from zero momentum (Figure 3). Furthermore, with active trunk flexion in the pre-extension phase, the sequence in which lower limb joints extended was knee, hip and ankle. When no trunk flexion occurred, however, the order of onsets was reversed, with the hip starting to extend before the knee. These findings illustrate how an anatomical connection between four segments can be turned into a functional linkage and suggest that movement of the trunk segment may augment force production in the extension phase by utilising the dynamic characteristics of the segmental linkage, for example, by utilising the stretch-shortening cycle (Cavagna et al 1977). Research into the stretch-shortening cycle has shown
that the greater the stretching contraction or eccentric work done (Bosco et al. 1982) and the shorter the time delay between eccentric and concentric contractions (Bosco et al. 1987), the greater the potentiating effect on the subsequent concentric contraction. That is, under these conditions, the following concentric contraction is more forceful and efficient. Active and relatively fast trunk flexion appears, therefore, to have a potentiating effect on extensor force production in the extension phase of the action, with the probability that relatively less muscle force need be generated.

Clinical implications
The results suggest that the ability of a disabled individual to generate extensor force and raise the body mass vertically in sit-to-stand can be optimised by: starting active trunk flexion in the pre-extension phase from the erect position in order to achieve the necessary horizontal momentum; ensuring the extension phase does not commence with the trunk stationary and flexed forward; and encouraging the individual to swing the trunk forward at a reasonable speed.

The contribution of the upper limbs to balance and propulsion
Standing up is commonly achieved with the upper extremities free. As a result, when necessary, the arms are free to assist propulsion by pushing on the arms of the chair or swinging forward. The arms may also assist in maintaining balance as they do in locomotor and jumping actions. Under certain circumstances, of course, the upper extremities may be functionally restricted, such as standing up while holding on to a tray. In this context the task requirements may well affect both balance and propulsion. It could be assumed that balance would be critical to sit-to-stand during the period that the relatively large upper body pivots over the fixed feet (extension phase).

It has been shown that, at thighs-off, the centre of body mass has moved forward over the feet (Carr 1992). This position ensures that the relative position of body segments at thighs-off enables lower limb extensor forces to accelerate the body vertically into the standing position.

The role of the arms during standing up was investigated by varying the extent of arm movement (Carr and Gentile 1994). Subjects stood up with arm movement: (a) occurring naturally; (b) functionally restricted (subjects held a rod while keeping their elbows in to the trunk); and (c) augmented (subjects pointed to a target as they stood up). Although subjects had no difficulty standing up while pointing or when the arms were restricted, variations in extent of arm movement did have an effect on the dynamics of the action. The results indicated that when the arms were restricted there was: (a) increased time spent producing a high level of extensor force throughout the lower limbs (support moment); and (b) decreased horizontal and vertical linear momentum of the centre of gravity. Furthermore, the shank continued to move forward on the foot for approximately 28 per cent of the extension phase.

These results suggest that subjects were less likely to risk projecting their body mass as far forward or move it as fast when the arms were restricted compared with when they were free to move. This may have been a strategy to avoid excessive perturbation and thereby minimise the balance requirements. The finding that the shank continued to move forward on...
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the foot in the early part of the extension phase means that the shank would not have been contributing to extensor force at thighs-off.

Clinical implications
It is common clinical practice to have individuals with hemiplegia hold the affected arm in front of the body with the intact arm (Bobath 1990, Davies 1985), thereby effectively restricting movement of both arms. The results of this study suggest that restricting natural arm use in this way may interfere with natural momentum of the movement and increase the time over which a high level of extensor force has to be produced by lower limb extensor muscles. Furthermore, the need to sustain dorsiflexion would be difficult for individuals with weak dorsiflexor muscles, eg following stroke.

The effects of foot placement on movement dynamics
It could be assumed that foot placement would be a critical factor for the ease of standing up, since it affects the distance forward over which the body mass has to move. Indeed, it is evident that under most conditions the feet are moved backward before the start of the action. Two recent laboratory studies showed that, in both young and elderly subjects, initial foot position affected both the pre-extension and extension phases of the action (Rajaratnam and Shepherd 1994, Shepherd and Koh 1993). In both studies, there were three foot placement conditions (Figure 4).

As the feet were placed further forward, it was apparent that the body mass was moved the greater distance forward by at least two mechanisms. There was a progressive increase in both the amplitude and the velocity of trunk flexion, which would have resulted in an increase in the forward momentum of the body mass. In addition, the ankle dorsiflexed throughout a longer proportion of the extension phase. As the feet were placed further forward, the pattern of force production through the lower limbs changed. Although the peak value of support moment remained relatively constant, peak moment at the hip increased while knee and ankle moments decreased. At thighs-off, the time around which peak hip, knee and ankle moments typically occur, the hip extensor muscles appeared to be the sole contributor to the propulsion of the body mass vertically when the feet were forward.

Clinical implications
It is evident that standing up with the feet forward does not allow for optimal performance and affects the ease of standing up, a factor of relevance to individuals with lower limb muscle weakness. The increased amplitude and velocity of trunk flexion at the hip and the considerable increase in force production at the hip at thighs-off has implications for individuals with musculoskeletal and neurological disorders. For these people, placing the feet backward may be critical to the ability to stand up independently. Training of sit-to-stand should involve consideration of foot placement and the rehabilitation and home environment should include seats which allow the feet to be moved back sufficiently to enable the action to be performed with relative ease.

Figure 4
Schematic of starting positions under each condition: FB= feet back; FP= feet preferred; FF= feet forward.

The effect of different movement speeds on movement dynamics
Although able-bodied individuals stand up at different speeds depending on the environment and goal of the action, the aged population (Alexander et al 1989, Rajaratnam and Shepherd 1994) and individuals with movement dysfunction have been found to stand up more slowly. For example, Ada and Westwood (1992) reported that, following stroke, individuals took an average of 2.3 seconds to complete the extension phase of standing up, whereas the time taken by able-bodied subjects ranged from 0.9 to 1.2 seconds.

The results of a recent study in which speed of movement was varied (slow, preferred, fast) indicated that when subjects moved fast the relationship between the displacement and velocity of trunk flexion changed, velocity increasing with a decrease in displacement. In other words, the faster they moved the less they flexed at the hip. The consequence of increasing the displacement of trunk flexion along with velocity would have been an excessive horizontal displacement of the body mass with adverse consequences for balance. Decreasing the amplitude of
displacement would, therefore, have prevented the body mass from being projected too far forward at the time when vertical propulsion commenced. A faster rotation of the large trunk segment would also have enabled an earlier transfer of the horizontal linear momentum into vertical momentum.

Not only did peak support moment increase as the speed of the movement increased but there also was a decrease in the duration of a high level of support moment (Figure 5). There was, therefore, a relatively short burst of extensor force propelling the body mass vertically rather than a more sustained effort when subjects moved slowly. This finding suggests that the speed of trunk rotation may play an important role in optimising force production in the lower limbs. One of the mechanisms potentiated may have been the stretch-shortening cycle.

**Clinical implication**

Individuals with movement dysfunction who move very slowly may need to be encouraged to move a little faster, in particular to swing the trunk forward more quickly to potentiate the effect of trunk flexion on lower limb extension.

**Conclusion comments**

It is clear that academic and clinical physiotherapists need to work together, combining their skills and opportunities in the manner most conducive to the development of physiotherapy (and movement rehabilitation) as a clinical science and, through this, to the development of clinical practice that is effective in optimising the motor performance of individuals with disability. Such collaboration needs to be actively promoted in hospital departments, in private clinical practices and in schools of physiotherapy.

Changing scientific attitudes and concepts are, typically, slow to carry over into practice. Nevertheless, the praxis-driven and person-oriented approaches to physiotherapy dominant for the past few decades are slowly being replaced by a more theoretically-driven rehabilitation process, with an emphasis on measuring functional outcomes. It is becoming clear that those who will guide physiotherapy into the future require a rigorous and relevant scientific preparation for clinical practice. The mechanism for such an education is already in place in Australia, with all physiotherapists entering clinical practice with undergraduate degrees and some going on to engage in graduate study. A specialisation process also is in place for clinicians who want to practice in a specific area of physiotherapy at a high level of skill and understanding.

The results of two recent surveys of physiotherapists working in neurological rehabilitation in Sweden (Nilsson and Nordholm 1992) and Australia (Carr et al 1994) suggest that a more scientific preparation of clinicians may lead to a more rational delivery of rehabilitation. There was a trend for the more recently educated Australian physiotherapists to be better able to describe the theoretical basis for their intervention. In addition, these physiotherapists were more likely to be using quantified measures to evaluate outcome.

Nevertheless, in the undergraduate programmes in the Australian system, there still can be a mismatch or incongruity between the biological and behavioural science subjects and the clinical subjects in which the traditional praxis-orientation may still be passed on to a future generation of practitioners. This typically occurs in neurological physiotherapy in which

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**Figure 5**

As speed of movement increased (a) support moment increased and (b) the time spent generating a high level of support moment decreased.
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Australia survey showed that hybridisation still flourishes. The Australian survey showed that hybridisation, or what could be called a “limited eclecticism”, still forms the basis of many educational programmes, praxis- and person-orientation being maintained through the combination of traditional physiotherapy approaches such as NDT/Bobath and PNF.

In a recent editorial (1994) on the future of neurological rehabilitation, the authors suggested that the slow pace of change in clinical practice “is nowhere more evident than in hospital-based rehabilitation departments themselves. Few would offer laboratory facilities, including technical staff, to enable the measurement of motor performance as a way of evaluating outcome. In addition, modern electronic devices are not in general use despite the fact that electronic assistance in motor training has been shown to be effective in both able-bodied and disabled subjects. It has been demonstrated, for example, that practising walking on a treadmill, if necessary supported by a harness, can have a positive effect on walking performance in individuals with disability (Malouin et al 1992, Visentin and Barbeau 1989). Practising sit-to-stand with the aid of an augmented feedback device assists people with stroke to optimise their performance on this action (Engardt et al 1993). Yet how many rehabilitation units have or utilise such apparatus. Furthermore, how many health systems have a career structure in place which enables rehabilitation units to attract appropriately qualified physiotherapists who will develop and test rehabilitation interventions, based on current scientific theories and sophisticated technologies”.

The future of physiotherapy in rehabilitation can be anticipated from both a negative and a positive perspective. The authors take the positive view, considering that physiotherapists are already showing signs of being more seriously committed to the process of rehabilitation, and are more prepared to subject that process to intelligent and thoughtful scrutiny, and to test the outcome of clinical hypotheses.

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