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An investigation of the action of the hamstring muscles during standing in crouch using functional electrical stimulation (FES)

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Abstract

The hamstring muscle moment arms indicate that they act as hip extensors and knee flexors. Previous work using induced acceleration (IA) analysis and functional electrical stimulation (FES) has, however, revealed counter-intuitive muscle actions, particularly for biarticular muscles during the stance phase of normal gait. In conditions such as cerebral palsy the hamstrings have been associated with the development of pathological gait patterns, particularly crouch gait. This study examines the role of these muscles in the control of crouched standing postures. Five unimpaired adult subjects had their muscles stimulated during quiet standing in different degrees of crouch. Kinematic and kinetic changes were observed and measured using a 3D motion analysis system. The hamstring muscles were shown to act strongly to retrovert the pelvis and extend the hip. The action at the knee changes as crouch increases, moving from flexing to extending.

Keywords: Electrical stimulation; Hamstrings; Crouch; Standing

1. Introduction

The hamstring muscles play an important role in normal gait. They are active from late swing phase into early stance, with activity continuing well into midstance in some subjects [1]. The muscles, except the short head of biceps femoris, cross both hip and knee joints. Their anatomical action as hip extensors and knee flexors mean that they are ideally placed to arrest hip flexion and knee extension at the end of swing phase. In stance phase, however, their action is more complex. Considering the two joints separately, the muscles have the potential to participate in active hip extension, restraint of knee hyperextension and initiation of knee flexion in loading response. Recent work using induced acceleration (IA) analysis has, however, highlighted the difficulty of using an intuitive approach when assessing muscle action, particularly for two joint muscles during weight bearing. Kimmel and Schwartz's [2] assessment of the long head of biceps femoris reveals such a strong extending action at the hip that it is more likely to cause dynamic knee extension than flexion, in early stance.

The hamstrings have frequently been implicated in the development of the pathological gait patterns seen in conditions such as cerebral palsy. Short or over-active muscles are thought to contribute to posterior pelvic tilt, excessive sagittal plane pelvic motion and the development of crouch. Classic texts of the late 1980s and early 1990s [3,4] recommend hamstring lengthening surgery to treat crouch gait, as part of a balanced package of multilevel procedures.

More recently musculoskeletal models have been used to assess the dynamic length of the hamstring muscles [5,6]. Delp et al. [6] reported that most subjects (80%) walking in crouch had hamstrings of normal length or longer, due to the relative muscle moment arms at hip and knee. These findings

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have had an impact on clinical practice, particularly in those centres with access to musculoskeletal modelling software (e.g. [7]). The wisdom of lengthening muscles which are already long has been questioned. The role of the hamstrings in promoting hip extension and combating excessive anterior pelvic tilt has also been highlighted [5].

Assessment of muscle length does not indicate whether the muscle is operating at high tension (active or passive) or what effect this force has on movement. IA analysis has a useful contribution to make here. IA techniques have been used to assess normal gait [2,8,9] but there are no published data for the hamstring muscles during crouch gait. There is, however, a danger of relying too heavily on the results from theoretical, model based approaches without practical validation.

Stewart et al. [10,11] investigated the dynamic action of the calf muscles using a combination of functional electrical stimulation (FES) and IA analysis. Both approaches, one practical and one theoretical, seek to predict the effect on the dynamics of the musculoskeletal system of a perturbation in muscle force. The two sets of results, when in agreement, provide strong evidence of muscle action.

This study seeks to explore the role of the hamstrings in crouch by using FES. Patients with crouch gait patterns have a range of different musculoskeletal deformities and co-ordination difficulties. For this reason non-impaired volunteers were used. The analysis was also performed for standing rather than walking, to give greater repeatability and experimental control.

2. Methods

Five non-impaired adult subjects volunteered to take part in the study, which was covered by local ethics committee approval. All gave informed consent. They were four males and one female, with an average age of 41 (34–50), height of 1.75 m (1.63–1.82) and weight of 87 kg (59–105).

FES electrodes (Nidd Valley Medical) were placed over the hamstrings bilaterally. For the lateral hamstrings the active electrode (cathode) was placed proximally on the lateral aspect of the thigh, over the long head of biceps femoris. The indifferent electrode was placed distally to this but proximal to the tendon. For the medial hamstrings the active electrode was positioned just medial to the posterior mid line of the thigh over the proximal portions of semitendinosus and semimembranosus. The indifferent electrode was placed distally to this, whilst ensuring that it was proximal to the tendon. The optimal positioning was determined by palpation. This was done with the subject lying prone on the examination couch. The positions of the electrodes in one subject are illustrated in Fig. 1.

Fig. 1. Illustration of hamstring electrode locations for one subject.

The stimulation waveform comprised asymmetrical biphasic pulses at 40 Hz with a maximum current of 70 mA. Pulse width was adjusted to produce a strong contraction in the muscle group whilst remaining comfortable. The force produced was typically strong enough to flex the knee against gravity. Isolation of the medial and lateral hamstring groups was verified for each subject by palpating the distal tendons whilst stimulating each muscle group in turn.

One limb was selected at random to determine which foot would be placed on the force platform. An electrogoniometer (Biometrics Ltd., Gwent, UK) was placed on the medial side of the knee on the same limb. The goniometer angle was available as a real time display on a laptop computer screen. This computer was placed in front of the subject, in clear view. A full lower body 3D marker set was then applied (Plug-in-Gait, Vicon). The Plug-in-Gait model was used to process the lower limb kinematic and kinetic data.

The subjects first performed a calibration test to establish the relationship between the electrogoniometer reading and 3D joint angle. The subject was asked to stand in a range of different postures, with a prescribed knee flexion angle, as observed from the goniometer output. Data were collected in 10° increments from 0° to 80°. The 3D data were processed allowing the equivalent angles to be calculated. A calibration curve was constructed by plotting the 3D angles against the electrogoniometer readings. This curve could then be used to read off the electrogoniometer equivalent of any 3D knee flexion angle.

Data were then collected for the subjects undergoing stimulation while standing in a crouch posture with one foot on the force platform and both feet flat on the ground. The medial and lateral hamstrings were tested separately with the order randomised. For each test the left and right limbs were stimulated simultaneously. Subjects were asked to stand in a range of postures (0°, 10°, 20°, 30°, 40°, 60°, or 80° of knee flexion). The order of the postures was randomised. The angles were set for the 3D system by asking the subject to adopt the posture giving the equivalent electrogoniometer reading on the visual display. Once a stable reading had been achieved the stimulation was applied after a random delay. The stimulation period was 1 s. The resulting movement was recorded using the Vicon system and Kistler force plate. The test was repeated six times for each muscle/posture combination.

3. Results

Table 1 gives the standing postures for each prescribed crouch angle. The electrogoniometer calibration has kept the mean knee angle within 1° of the target across the range of values tested. The standard deviations were also small, at around 2°. Subjects increased their ankle dorsiflexion and hip flexion in order to achieve the required posture. Pelvic tilt decreased from 0° to 40° of crouch and then increased again. This is a reflection of the trunk lean required to achieve balance. There was more variability in the angles of the pelvis, hip and ankle than the knee, as seen in the higher standard deviations. Different subjects adopted slightly different limb alignments in order to achieve the required degree of crouch.

Fig. 2 shows the standard report format prepared for each subject and for both muscles. This figure gives sample results for subject 3, when his lateral hamstrings were stimulated. Each trace is the mean of five separate trials. The angles are displayed for 1 s before stimulation, the 1 s stimulation period and 1 s after stimulation, with a vertical line marking each transition. These results are fairly typical of the group. The stimulation causes the pelvis to tilt backwards, the hip to extend and the ankle to dorsiflex. The effect at the knee is posture dependent. Stimulation causes knee flexion in mild crouch but this effect diminishes, or even reverses, as the degree of crouch increases. The perturbed motion generally reduces as crouch increases.

The effect on the ground reaction force (GRF) is more difficult to interpret. The traces here have had the offset for quiet standing removed to show the changes more clearly. Whereas the kinematic change is generally in one direction, the GRF components show more oscillation. This is predictable as a sustained force would lead to sustained acceleration and instability. In this subject there does seem to be a consistent anterior GRF (positive AP component) immediately after stimulation.

For five of the 10 subject/muscle combinations a small angle change was observed on the knee graph before the main trend developed. Only one or two postures were affected in each case. This can just be observed on the graphs in Fig. 2 and is clearest on the bottom curve (neutral alignment). The change was very small, typically 1° or 2° in the direction of extension and lasted around 100–200 ms. Several possible explanations for this were explored. A genuine change in joint angle could have taken place, resulting from a change in muscle action or a reflex response in the quadriceps. Alternatively the change could be an artefact arising from skin movement or modelling errors in joint centre location.

One subject had a repeat test with EMG electrodes placed over the quadriceps (vastus lateralis and medialis and rectus femoris) during the testing protocol to investigate any increased activity, either from reflex activation or volitional action. The presence of a stimulation current does limit data collection as EMG signals can only be examined between the pulses, allowing for amplifier recovery. Within these constraints no additional activity was detected in the quadriceps.

The effects of model assumptions and skin movement were also explored. The thigh marker was observed to move in some subjects as the hamstring muscle belly changed shape on stimulation. The pelvis also tended to move first and an incorrect location of the hip joint centres could produce an apparent tilt of the thigh segment, and hence knee extension. The small magnitude of the potential artefact made investigation difficult. For one subject additional, alternative thigh and shank markers were added. For all subjects a range of knee flexion angles was produced from 2D projections of different combinations of markers. In each case it was possible to eliminate the movement in this way, though the strategy used varied.

Table 1
Standing posture for the five subjects immediately prior to stimulation. Only the knee angle was under active control

	Theoretical knee angle						
	0°	10°	20°	30°	40°	60°	80°
Pelvic tilt							
Mean	9.9	8.4	7.8	6.6	5.5	8.0	14.0
S.D.	(4.0)	(4.4)	(4.0)	(4.5)	(5.6)	(7.6)	(8.2)
Hip flexion							
Mean	5.2	8.7	13.2	17.0	21.4	35.1	55.4
S.D.	(5.3)	(5.0)	(4.3)	(5.6)	(7.1)	(10.3)	(11.6)
Knee flexion							
Mean	0.5	10.6	20.8	30.7	40.8	61.0	80.6
S.D.	(2.2)	(1.3)	(1.6)	(1.8)	(1.3)	(1.4)	(2.2)
Ankle dorsiflexion							
Mean	3.9	9.2	14.8	19.4	23.9	32.5	36.5
S.D.	(2.3)	(2.5)	(2.2)	(1.8)	(2.4)	(4.2)	(6.0)

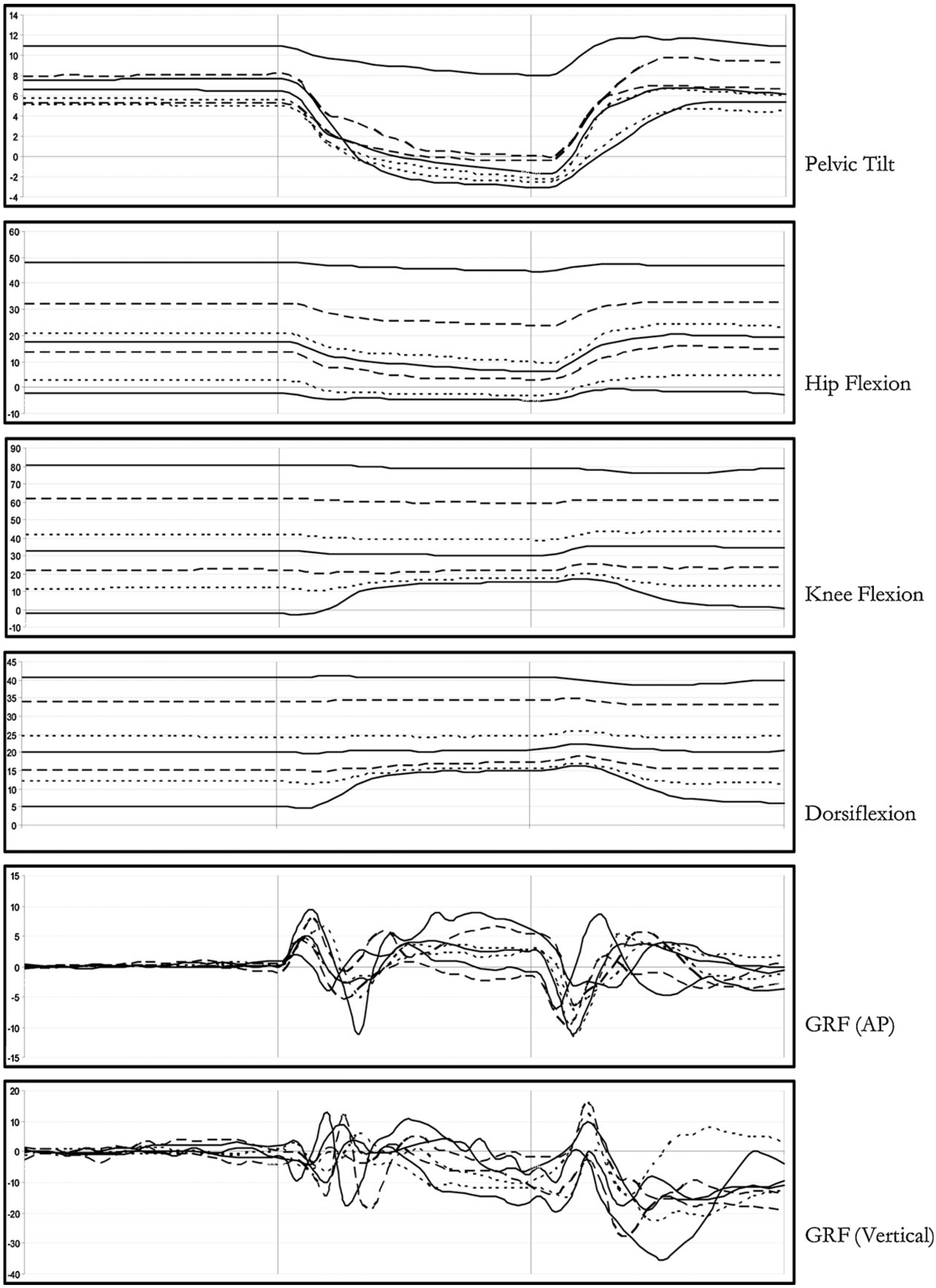

Fig. 2. Sample data for one subject with lateral hamstrings stimulated. Each trace is an average of five trials. The time period is 1 s pre-stimulation, 1 s stimulation, 1 s post-stimulation.

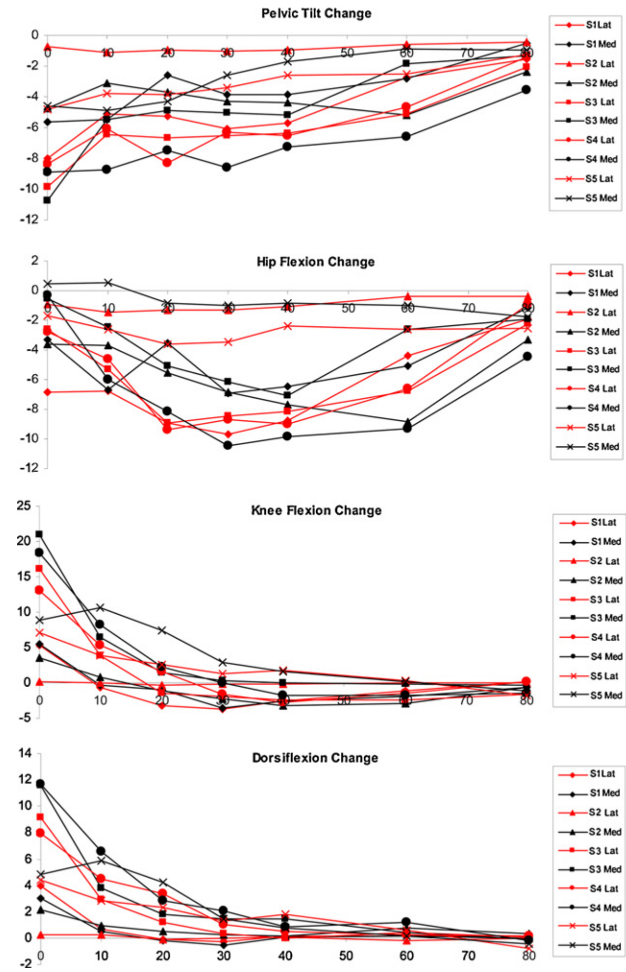

Fig. 3. Summary results for all five subjects showing the kinematic changes following stimulation of the medial and lateral hamstrings separately. The x-axis gives the angle of knee flexion for the standing posture immediately prior to stimulation. Each point on the graph is an average of five trials. The reference points for calculating the change were immediately prior to stimulation and 0.5 s after onset.

Overall it was felt that the small additional movement observed was unlikely to represent the main muscle action, or that this action would then change. The 2D projected estimations suggest that it is a marker/model artefact.

Fig. 3 shows the summary results for the whole group. The x-axis gives the prescribed knee angle and the y-axis gives the angle change at pelvis, hip, knee and ankle. The change in angle was measured from just before the onset of the stimulation, to the midpoint (after 0.5 s). Similar patterns are observed across the group, as were seen for one subject in Fig. 2. Hamstring stimulation leads, almost universally, to posterior pelvic tilt and hip extension.

The effect at the ankle will depend on the exact combination of movements of the more proximal segments. The predominant effect is dorsiflexion.

The effect at the knee is particularly interesting. In an upright posture hamstring stimulation produces knee flexion. As the degree of crouch increases, however, this diminishes and even reverses. Some subject/muscle combinations show a knee extension action by 20° of crouch and this is the predominant pattern within the group by 60°.

4. Discussion

Across the group general trends emerged. The hamstrings have a retroverting action on the pelvis at all postures. The hip extends, in line with the anatomical action. These actions generally led to the greatest changes in joint posture, particularly in the mid range of crouch (knee flexion 30–60°). This highlights the role of the hamstrings in controlling pelvic posture. In children with cerebral palsy excessive anterior pelvic tilt is frequently a problem and the hamstring muscles are key to combating this deformity.

Crouch is generally described by referring to the degree of knee joint flexion. The action of the hamstring muscles at the knee is therefore of particular interest. At low knee flexion angles the hamstrings act, as predicted, as knee flexors, however as the posture moves towards increased crouch the action tends to reverse to one of extension. There was some variability within the group in the angle at which the action changed. The action at the knee arises from the net effect of two opposing actions. The hamstring moment arm at the knee will produce a joint moment tending to promote crouch, whereas the moment at the hip will promote limb extension.

The evidence presented in this paper suggests that, while the hamstrings have a role in initiating knee flexion from a neutral standing posture, they do not go on to exacerbate the crouch at higher knee flexion angles. In fact they may even work to combat more extreme crouched postures.

This study has looked at the effects of hamstring stimulation in unimpaired adults adopting a standing posture. The main clinical application is to children with cerebral palsy walking in a crouched posture. Extrapolation of the results to this population involves three main assumptions: firstly that the results would be the same for children as adults; secondly that the other features of the pathology can be ignored and thirdly that standing is an appropriate model for assessing gait. In the light of these significant assumptions the parallels drawn can only be tentative.

Arnold et al. [12] list several potential causes of crouch gait, including short or spastic hamstrings, weak plantar flexors, bony torsion, tight hip flexors, weak hip or knee extensors and poor balance. Our findings suggest that excessive force in the hamstrings is unlikely to cause ever increasing crouch. In fact weakness of the hamstrings, in their role as hip extensors, is more likely to be responsible. It is possible, however, that the action of the hamstrings in initiating flexion may start a process, which then escalates due to the other factors listed, in combination with the increasing weight of the growing child.

The results of this study need to be considered in the light of any possible limitations and uncertainties. The trends observed in the data from the five subjects were reasonably consistent (see Fig. 3). The magnitude of the angle changes did vary between subjects. This is expected due to different tolerance thresholds to the stimulation. Some subjects did, however, display a small extra extension excursion at the knee joint at the onset of stimulation. This has already been discussed and a likely explanation suggested. It is possible, however, that the observation is a genuine effect which has yet to be fully explained.

The approach adopted in this study assumes that the stimulation leads to a discrete, isolated increase in force in the selected muscle group. While the stimulation parameters can be tightly defined, the same is not true for the muscle force. The stimulation current will cross anatomical boundaries, potentially affecting other muscles, nerves and reflex arcs. Once the force has developed, soft tissue interconnections may lead to attenuation of the force between the muscle belly and the origin and insertion points, with tension being transmitted to adjacent structures.

As far as possible these effects were assessed and minimised. Fortunately the hamstrings are large muscles, so the stimulation current would have to travel some distance before reaching other structures. The current reaching other muscles should not have had a significant effect in terms of force generation. This was checked by palpation on the examination couch. In every case the dominant movement observed when the muscle was stimulated on the couch was knee flexion. A small amount of hip internal rotation was also observed in some cases. As mentioned earlier one subject had quadriceps EMG collected during the test protocol and no additional activity was recorded on stimulation.

Further work is now required to extend this investigation of the action of hamstring muscles. In examining the calf muscle action [10], subsequent confirmation using induced acceleration (IA) analysis proved useful [11]. This approach can also be applied here. There is also a need to conduct a study stimulating the hamstrings during gait in unimpaired subjects and children with cerebral palsy. This would allow the tentative conclusions suggested above to be tested more fully.

5. Conclusions

In normal, quiet standing hamstring muscle action will lead to pelvic retroversion, hip extension, knee flexion and ankle dorsiflexion. As subjects adopt an increasingly crouched posture the action on the pelvis and hip is preserved. The action at the knee, however, changes from flexing to extending. These findings have implications for our understanding of pathological gait patterns, particularly the development of crouch in cerebral palsy. Further investigation is now required to deal with any outstanding uncertainties, to explore the theoretical foundation of the observations (using techniques such as induced acceleration analysis) and to extend the practical work to cover dynamic activities and pathological movement patterns.

Conflict of interest

None.

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