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Biomechanical Analysis of Functional Performance During a Chair Rise Task

Before and After Participation in an Exercise Treatment Program

Alberto Esquenazi, MD, Mukul Talaty, PhD, Mary Klein, PhD MossRehab Gait and Motion Analysis Laboratory Philadelphia, PA USA

In previous research, we have determined that shoulder pain is a common problem in the post-polio population. This pain is thought to result, as least in part, from repetitive use of the arms to assist with weight-bearing during mobility and transfer activities when there is significant weakness in one or more of the muscles in the lower extremities. The increased stress on the upper extremities during these activities results in symptoms of shoulder overuse. The purpose of this project was to study the implications of shoulder dysfunction in the lives of polio survivors, in terms of effects on functional performance and quality of life, and to determine whether these factors can be significantly improved as the results of a rehabilitation program. We examined the use of an individualized exercise program as a potential means of reducing the burden of both primary and secondary impairments in post-polio and looked at whether it was an effective treatment for improving function, biomechanics of sit to stand and quality of life.

Rationale:

Understanding how strengthening affects the biomechanics of task performance in the presence of pathology can clarify the role of strength changes in improving function. Therefore, the major focus of this study was to determine how changes in strength and resolution of musculoskeletal symptoms due to an exercise program would affect functional performance associated with standing from a chair. It was assumed that the custom exercise program would increase strength in the upper and/or lower extremities and would simultaneously reduce shoulder symptoms.

Specific Aims:

1. To determine if an exercise program will improve the ability to perform a common functional task (chair rise) in terms of time to complete the task and lateral symmetry of kinematic and kinetic variables.
2. To determine the effect of an exercise program on upper extremity loading patterns.

Hypotheses:

1. Increased lower extremity strength will result in the lower extremity carrying more of the load to propel the body during the sit-stand task. Correspondingly, upper extremity forces should be reduced.
2. Increased lower extremity strength will give rise to less forward trunk lean, earlier arm release, and less forward and/or upward velocity. These are stability and propulsion compensatory techniques that may be less necessary with increased lower extremity strength.
3. Decreased upper extremity symptoms will be reflected in increased agonist upper extremity EMG due to more dependence on upper extremity muscles and less dependence on upper extremity passive tissues. Specifically, we predict an increase in triceps and post-deltoid and maybe lateral deltoid electromyographical (EMG) activity.

Inclusion/Exclusion Criteria:

Polio survivors who did not wear a locking knee brace (caliper) and were enrolled in one of the protocols of upper and lower extremity strengthening, or relaxation group in a separate symptoms related study were eligible to participate in this study.

Subjects:

There were a total of nine polio survivors enrolled who provided written informed consent prior to testing. Subjects participated in a combined upper and lower extremity strengthening group or a relaxation group as a treatment intervention.

Demographics	Gender	Post-polio
Age (yr)	M	62.56 (8.3)
	F	62.31 (8.2)
Height (in)	M	68.29 (3.2)
	F	63.02 (2.8)
Weight (lb)	M	187.18 (38.9)
	F	154.71 (31.6)
BMI	M	28.12 (4.5)
	F	27.20 (5.1)
SPADI Rating		
Ave. Pain	M	22.86 (17.3)
	F	24.81 (20.7)
Ave. Dysfunction	M	28.58 (25.8)
	F	36.56 (31.9)

Methods:

Data collection and analysis procedures were followed as outlined in previous publications. Contact forces between the feet and the ground and contact forces between the arms and the armrests were recorded with 4 AMTI specially designed force platforms (2 on the floor and two on the chair armrest, bilateral surface EMG of six muscles in each arm using a Motion Lab System, and full body 3-D movement data were simultaneously collected with 2 CODA mpx 30 optoelectronic systems and 48 active markers. **(fig.1)**

Fig.1 Patient set up for data collection

Prior to data acquisition, arm strength data were recorded at 30% of maximal effort. The methods were devised to allow quantitative assessment of changes in muscle activity due to the exercise program. The basic premise was that the dynamic EMG (i.e. that recorded during sit-stand performance) from each test session was normalized to the EMG from the subject's sub maximal effort. Doing so accounted for many of the factors that produced variability and normally impede comparison of EMG across test sessions. A sub maximal level has been reported to be ideally useful for intersubject comparison across sessions. The 30% level was selected as it was anticipated to be safe and one that the subjects could attain and hold without much difficulty or practice. A hand held dynamometer with real-time digital readout was used to assess the force level achieved by the subject. A contact switch was manually triggered when the subject obtained the desired level to allow identification of the EMG record to use during data processing. EMG activity was recorded for three repetitions from each muscle at the 30% level. A standardized procedure to isolate each muscle being tested was followed based on recommendations for muscle testing. Isolation was critical to minimize the ability of substitution of muscles other than the one being tested to contribute to the target force.

Normalizing the dynamic EMG recordings to the subjects' sub maximal level framed the dynamic EMG in terms of "effort". The "units" of the normalized dynamic EMG signal were then relative to the EMG created by the subject's 30% effort for each muscle.

Data Analysis:

Because of the small sample size, formal statistical analyses were not possible. Instead, data from pre and post-intervention were compared and trends were noted.

Results:

The results indicated that symptom severity improved in all subjects from this study who participated in one of the exercise programs. Four out of six subjects who participated in one of the exercise programs also showed an increase in overall lower extremity strength. None of the subjects in the relaxation program showed any change in overall lower extremity strength or overall upper extremity strength.

There was some evidence that the increase in lower extremity strength was associated with upper extremity unloading, but there was no evidence of a consistent shift in load towards the strengthened lower extremity areas. Many of the subjects with increased lower extremity strength also displayed increased forward trunk lean. Arm release timing and trunk velocity changes were mixed.

Muscle activity in one or more of the major upper extremity muscles that provide propulsion during sit-stand (posterior deltoid, triceps, lateral deltoid) were increased for all subjects who displayed upper extremity symptom reduction. Decreased co-contraction was observed in one or more of the upper extremity agonist-antagonist pairs for all study subjects for whom upper extremity symptoms resolved as well as for the subjects for whom symptoms did not change.

Discussion:

The trend towards decreased upper extremity forces with increased lower extremity strength suggests that strengthening the leg muscles may have contributed towards unloading the arms. However, lack of consistent changes in the lower extremity forces suggested that leg loading was not altered with leg strengthening. The abbreviated duration of the arm use during the sit-stand task, relative to leg use, may help to explain why there was evidence of upper extremity unloading without lower extremity loading changes. It is possible that the lower extremity forces increased during the brief time when the arms were being used.

Another possible explanation for the decreased arm loading by unchanged leg loading stems from the trunk use strategy. 75% of subjects with increased lower extremity strength also showed increased forward and/or upward velocity, which suggests that they used momentum rather than pushing through the legs to assist in propulsion.

The EMG data were found to be sensitive to the exercise intervention and were supportive of the a-priori hypotheses about mechanism of change.

Decreased upper extremity symptoms were associated with increased agonist EMG during sit-stand. Combinations of the triceps, posterior deltoid, and lateral deltoid muscles showed increased activity in all subjects for whom upper extremity symptoms resolved. This finding provides some evidence of increased use of active tissue during the sit-stand task.

KEY RESEARCH ACCOMPLISHMENTS

- Through this research, we were able to determine that musculoskeletal pain in polio survivors is more closely related to activity intensity, rather than activity frequency. Polio survivors push themselves to maintain activity levels that are comparable to older adults without a history of polio. However, since the polio survivors' maximum performance capacity is lower, the difference between their normal performance level and their maximum performance level is smaller. Therefore, they are at higher risk for overuse problems.
- The results of this study confirmed the link between lower extremity weakness and upper extremity overuse among polio survivors.
- Through a detailed biomechanical analysis, we did not find support for the hypothesis regarding the correlation between leg strength and changed biomechanics in the sit stand task. Instead, there seemed to be a better correlation between shoulder symptom resolution and changes in biomechanics.
- The results of this study help to confirm the relation between lower extremity weakness and shoulder symptoms among polio survivors. Knee extensor strength was identified as an important predictor of shoulder symptoms, with polio survivors with combined knee extensor strength of less than 59 lb. at highest risk for development of shoulder symptoms. Polio survivors were at higher risk for development of overuse symptoms than the strength-matched controls.

CONCLUSIONS

Both exercise and relaxation therapies that focus on reducing the stress related to lower extremity weakness might reduce shoulder overuse symptoms. The results of this study have important implications for polio survivors and others with lower extremity weakness, who rely on their upper extremities to assist with weight-bearing during mobility-related activities. Increased leg strength allowed subjects to use a mix of strategies to increase propulsion while decreasing arm effort. These strategies included a mix of increased trunk lean and increased trunk velocities. The combined leg and arm exercise group was the only one to show relatively large improvements in both shoulder pain and disability. Further study with larger sample sizes is needed before any definitive conclusions about the changes in biomechanics associated with the intervention program can be drawn. Older adults are often encouraged to be as active as possible in order to maintain their functional independence for as long as possible. However, for polio survivors, there appears to be a fine line between activity levels that are beneficial and help maintain strength versus those that cause overuse problems and result in a further deterioration in strength.

Educational Manual Produced:

S.O.S. Save our Shoulders: A Guide for Polio Survivors. Philadelphia, PA, June 2003. Klein, Esquenazi and Keenan. (Manual was developed as a reference tool for our post-polio subjects and is available in English and Dutch as a PDF download from http://www.einstein.edu/rx_files/yourhealth/mrri_sos9510.pdf

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The Sheba Medical Center

Motion Analysis Laboratory

Uri Givon MD, Medical Director. Motion Analysis Laboratory and Human Performance Centre. Sheba Medical Centre. Tel Hashomer, Israel.

The Sheba Medical Center motion analysis laboratory was planned for a long time, and opened after a long process of research and selection. The aim was to establish a motion analysis laboratory that will serve all the hospital wards, orthopaedic, neurological, rehabilitation and others. Another aim was to create an excellence center serving the rehabilitation needs of the country, combined with virtual reality and isokinetic abilities. When the strategic decision to build the laboratory was made, we began to wrestle with the system selection.

There are two possible methods to select a medical system: one is the feasibility research approach and the other is the project team approach. The project team approach was selected for several reasons: we wanted all possible users of the laboratory to influence the selection process, and to motivate them to use the system later.

In order to understand the process better, one has to learn a little about the Sheba Medical Center. Established in 1948 as a military hospital, the medical center quickly became one of the leading hospitals in the country. For many years it inhabited WW2 era Nissen huts, in which cutting edge medical technology was put to use. In the last 3 decades a large rebuilding process has taken place, and the hospital wards were moved to modern buildings. The hospital is the largest in the country, and is divided into 2 main divisions: the general hospital and the rehabilitation hospital. The motion analysis laboratory was planned and created as a joint enterprise, located in the rehabilitation hospital, but involving general hospital personnel.

The selection process:

A committee comprised of the potential users of the laboratory and headed by the director of the rehabilitation hospital was set up. The committee included two paediatric orthopaedic surgeons, the directors of the orthopaedic rehabilitation and neurological rehabilitation wards, a neurologist specializing in movement disorders, the head of the physical therapy service, a physical therapist with gait analysis experience, the hospital engineer, two members (bioengineer and physiotherapist) of the School of Health Sciences in the Tel Aviv University and an administrator. The committee had multiple sessions discussing the needs and possible uses of the laboratory, defined the characteristics of the necessary system, and then reviewed the commercially available systems.

The head of the team served as the devil's advocate in most discussions, creating a challenging discussion that covered most possible problems. Every member of the team had to present his opinion on every subject, and to support it with references and proven facts. The discussions held in the committee meetings were sometimes heated, but most decisions were reached unanimously or with a very clear majority.

After reviewing the needs of the system and the experience of another hospital in the country that purchased a laboratory, the committee has decided that only an active marker kinematic system would be versatile enough to serve all the needs raised in the preliminary discussions. We reviewed the available active marker systems, and chose the Coda CX-1 system.

The Laboratory:

The walkway is 11 meters long with four AMTI force plates installed in it, making it the longest Coda system in the world. Six Coda CX-1 sensors cover the walkway, and two of them can be detached and taken on tripods to field studies or to another room in the laboratory. We added a Noraxon surface EMG system, and a pedobarograph system was purchased as well.

Continued work has progressed with the Charnwood staff in order to iron out software problems. Currently the system cannot support all 4 force plates automatically, and we have to use a "cut and paste" process to create a full report. A new version of the software that will allow simpler report generation is being developed.

The laboratory is part of a larger research and treatment facility, which includes a virtual reality laboratory based on the CAREN system (Motek, Amsterdam, Netherlands), and an isokinetic examination and treatment machine (Cybex). The planned strategy for the new facility is to provide diagnosis and treatment planning through the motion analysis laboratory, virtual reality system and the isokinetic laboratory, and treatment through the virtual reality laboratory and the isokinetic laboratory. The combination of all these modalities in one facility will provide an overall service to patients with motion disorders or needing rehabilitation after a musculo-skeletal or neurological disorders.

The Staff:

The laboratory team includes two physiotherapists, a technician and a physician. A bio-engineer joined us as a consultant recently. More personnel, such as a kinesiologist and other therapists, will be required in the future, and we hope to be able to hire them when the time comes. Several physicians take part in the motion analysis process, referring patients and planning research projects.

Motion analysis in Israel

Gait and motion analysis studies, as necessary as they are, are not covered by the Israeli health system. Currently we are scrutinizing possible income sources and grants to allow continued use of the laboratory. The committee is continuing it's work, planning possible uses for the facility, to persuading third party payers of it's importance and potential. Potential clients for the laboratory, other than the classical gait analysis in cerebral palsy, are amputees, patients with multiple sclerosis and stroke patients being treated in the hospital.

Several projects are being planned in the laboratory:

1. Gait evaluation of amputees following rehabilitation
2. Gait evaluation of long term amputees (over 60 years)
3. Gait evaluation of multiple sclerosis patients with variable disability profiles
4. Upper limb motion in PC users

Plans for the future

The aim of the laboratory is to assist the most under-privileged population in Israel, children and adults with cerebral palsy, patients after stroke and after amputations, with multiple sclerosis and other neurological disorders. Currently we cannot treat these patients based on scientific tests but on an educated guess, and the establishment and continues function of the Sheba Medical Center Motion Analysis Laboratory will change this situation. We hope to create an excellence center in the research, diagnosis and treatment of disorders of the human motion system.

Mobile Gait Laboratory

A Rewarding First Year's Experience

The Central Remedial Clinic (CRC) in Ireland is a national centre for the assessment and treatment of adults and children with physical disabilities. All services required by a person with a physical disability, ranging from medical to social and technical are provided from CRC's main centre in Clontarf, Dublin. CRC also provides disability services locally in the South East of Ireland and some specialized services in the Mid West. One of the specialized services offered at the CRC is clinical gait analysis. Up to recently children from all over Ireland had no choice but to travel to Dublin to access this service. This often involved an arduous and expensive journey for children and their families, which sometimes posed problems with compliance and obtaining accurate data. These problems were unacceptable in some cases especially when surgical decisions were being made based on the data. Establishing permanent gait laboratories in remote regions to make this specialized service more accessible would have been extremely difficult and economically unjustifiable. As a solution, CRC established what is believed to be the world's first truly mobile gait analysis service, which was reported in Motion Times in 2004. This article outlines briefly an update of the first year's experience with the service.

To date 11 outreach clinics have been conducted, 8 of these in the Mid West of Ireland in Limerick and 3 in the South East in Waterford. In total 54 assessments have been conducted. The clinics in Limerick are conducted in St. Gabriel's Centre, where CRC owns a large building from where it provides specialized seating services. A very large room is made available to the gait laboratory team for each clinic. In the beginning the fifteen meter, sectioned fiberglass walkway was used, but, because CRC owns the building in Limerick, a pit and dummy filler box were designed and now the portable force plates are inserted into the concrete floor during each clinic. The situation in Waterford is very different in that the mobile gait lab sets up in a postgraduate teaching room in the centre of a large and busy acute hospital. This is a second floor room which is booked for two days at a time in advance of a gait analysis clinic. The portable walkway is necessary in this situation and is housed permanently in a storage area in Waterford. All equipment is transportable in a saloon car and the full 3-D kinematic, kinetic and EMG system is replicated in the mobile service. A typical clinic would involve driving down to Limerick from Dublin (~160 miles) early on a Monday morning, setting up before lunch, seeing clients on Monday afternoon and on Tuesday and then driving back to Dublin on Tuesday evening. One car travelling with two people staying one night away limits the cost of each clinic to ~ €700. If you take an average of four to five full clinical gait analysis assessments per clinic then this represents very good value indeed.

There have been very few technical problems encountered with the system so far. Force plate noise was a problem at one stage but a change of power leads and some software adjustments have successfully addressed these issues. The laboratory's quality assurance procedures are conducted regularly on the mobile setup and testing to date has been very satisfactory. Patients with the same marker setups have been run through both systems and these tests were also satisfactory. Further testing of subjects using both the permanent lab and mobile lab setups simultaneously is planned in the near future.

The most immediate and real tangible effect of the mobile gait laboratory is the abolition of the need to travel to Dublin for 54 families so far. This fact has been acknowledged and praised by the Irish Health Services Executive through a spokesperson in the Mid West. Feedback from parents of children has been very positive and overwhelming so far and they are absolutely delighted at not having to travel to the capital city. Parents have commented on the costs involved in obtaining babysitters, taking time off work, travel costs to Dublin, accommodation costs as well as negotiating traffic in the city etc. Indeed, the Irish Minister for Defence, Willie O' Dea, praised the project for finding a low cost solution to providing a specialized medical service locally to the regions and wished that it could be replicated in other areas of medicine such as cancer services.

A second and very real effect of the mobile service has been the linking in with local clinicians and therapists. Whilst the service was always available at a national level it was seen as something difficult to access due to its centralised location in the capital city. In addition gait analysis was viewed as a complex new technology which required great effort to develop an understanding of the output. As part of the mobile gait analysis service the gait laboratory team has presented lectures and workshops to local therapists and clinicians, some via video conference. This has resulted in an upsurge in enthusiasm and a development of understanding amongst local clinicians and therapists in relation to the usefulness of the gait analysis reports in the management of their patients. The net effect has been an increase in referrals from these regions and a noticeable improvement in the reasoning process behind the clinical questions being asked in the referral letters. The gait laboratory recently delivered a one day course in the Mid West at the request of local therapists. Many therapists are now visiting the mobile clinics when their patients attend and one potential use of the videoconference aspect of the mobile lab is for local therapists to be able to sit in on Prof. O' Brien's clinic and partake in the discussions on their patients. This increased communication with local therapists and clinicians in the regions allows a dissemination of the specialized knowledge base which has built up in the CRC gait laboratory over the last sixteen years and can only result in an improvement of the quality of health care delivery for local patients.

There were also some unforeseen benefits to the mobile gait laboratory. A research project was undertaken this year by the gait laboratory looking at gait in Charcot Marie Tooth disease. There were a low number of volunteers for this study who were spread out around the country. Whilst some of these subjects were willing to partake in the study they were not willing to travel to Dublin. Therefore these subjects were analysed in the mobile clinics and this greatly increased the subject population for that study. In another project the CRC building in Clontarf is currently undergoing major internal renovations and refurbishment. The gait laboratory in Clontarf is due for expansion of office space and a relocation of toilet and changing areas. This necessitates the gait lab becoming a building site for three months. The only option would have been to close the service. However, the mobile lab will now be set up in a large room in a different area of the CRC and will continue to provide a gait analysis service while the renovations are taking place.

The service was officially launched in Limerick on April 12th this year by the Irish Minister for Defence and local government representative, Willie O' Dea, who praised the efforts of CRC in delivering this specialised service to the regions. Bernard Gloster, Health Executive manager in the Mid West, commented on the immediate impact which the service had on local patients and their families. The launch was well covered by the Irish national media and RTE's Nationwide programme filmed for a seven minute piece to be broadcast later in the Summer.

At the launch of the Liimerick Clinic, Irish Minister for Defence Willie O'Dea (left) with Mike Walsh the CRC's Gait Laboratory Manager and Darragh Costello, their first client, happy to demonstrate that technology for gait analysis is not restricted to one location, thanks to the foresight of CRC Dublin.

The gait laboratory have submitted a paper on the mobile lab to the European Academy of Childhood Disability meeting in Monaco this year and recently presented a paper at the Coda Users group meeting in Guy's hospital in London.

The impact on gait laboratory staff has meant a slight change in working practices. Up to now staff were permanently based in Dublin. Now they are required to travel on a six weekly basis, on average so far, to conduct mobile clinics. The clinics themselves are work intensive and physically demanding. To balance this the work is stimulating and staff are gaining much satisfaction from dealing with clinicians and therapists new to the technology and the clinical benefits of objective gait analysis. Additionally, the positive feedback from clients and their families is overwhelming. As a result of a predicted rise in referrals the gait laboratory is classified as a developing service and will receive priority for consideration for any new increases in staffing resource within the clinic.

The next step for the mobile gait laboratory is to consolidate the service now established in the Mid West and South East of the country and to provide more educational workshops and lectures to the clinicians and therapists in these regions. There have been some informal inquiries from people on the ground in the North West of the country, from counties like Donegal and Sligo and this would be the next natural region in which to develop a mobile gait analysis service.

Motion analysis and ultrasound: Techniques for measuring muscle and tendon function

Glen Lichtwark* & Alan Wilson#

** Institute of Orthopaedics & Musculoskeletal Science, Royal National Orthopaedic Hospital, University College London, UK.*
 # Structure and Motion Laboratory, Veterinary Basic Sciences, Royal Veterinary College, UK.

Traditionally, gait analysis techniques including 3D motion analysis, force plate measurement and electromyography (EMG) have been used to assess motion, but these techniques tell us very little about exactly how the muscle and its associated tendon (muscle-tendon complex, MTC) interact to produce the forces required for controlled and powerful movement. The MTC interaction during locomotion is critical for both force production and economical movement. Sonomicrometry studies have revealed that compliant tendons can store and return elastic energy to change the timing and magnitude of muscular work and allow the contractile components to act nearly isometrically, despite substantial length changes in the muscle-tendon unit [1]. This produces higher forces and reduces the energetic requirements of the muscle fibres. Similar results have been reported for human muscle fibres using ultrasonography during slow walking [2].

Here we have developed some novel techniques combining motion analysis and ultrasound that have allowed us to characterize the material properties of the muscle tendon unit, and also assess the interaction between a muscle and its attached elastic tissues (tendon and aponeurosis) during dynamic movements. Using ultrasonography we were able to image both the medial gastrocnemius muscle-tendon junction and muscle fibres themselves during dynamic activities such as walking and running on a treadmill and also one-legged hopping (Figure 1).

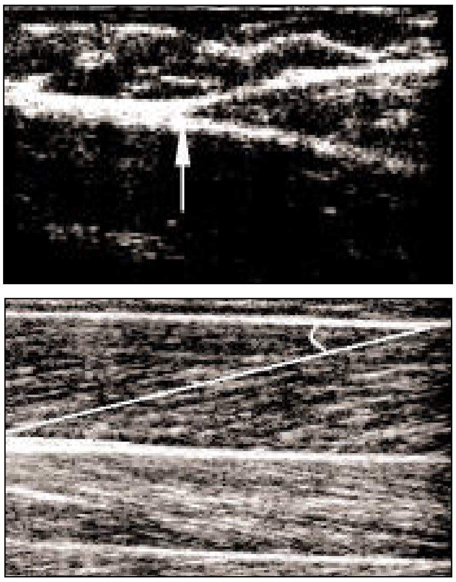

Figure 1: A) Ultrasonic image of the gastrocnemius muscle-tendon junction. The Achilles tendon is the white structure to the left of the arrow and the muscle is the within the white branches to the left the arrow. B) Ultrasonic image of the gastrocnemius muscle fibres (indicated by white line). The soleus muscle fibres are also visible below the lower muscle fascia, oblique to the gastrocnemius muscle fibres.

We used synchronous real-time ultrasonography and motion analysis to assess length and architecture changes of the gastrocnemius muscle fibres during walking and running on a treadmill. This gave us a more precise understanding of normal muscle fibre function and control during these movements. In particular it showed that the muscle fibres actually act isometrically or shortened during the stance phase of gait, when the whole muscle was lengthening (Figure 2a & 2c). Therefore the muscle fibres acted to stretch the series elastic components (the Achilles tendon and aponeurosis), which rapidly recoiled during take off (Figure 2d). In addition, it showed that the muscle fibres do change orientation considerably during contraction (Figure 2b). There is considerably more shortening of the muscle fibres during running compared to walking.

In addition we have used motion analysis markers to track the position of our ultrasound images in the laboratory frame of reference. This allowed us to project two-dimensional measurements (2D) from the ultrasound images into the three-dimensional (3D) space of the laboratory. In this fashion we tracked the position of the muscle-tendon junction from our ultrasound images and synchronously projected these into the 3D space (Figure 3). A measure from this point to the insertion of the tendon (the calcaneous) was used as a measure of Achilles tendon length. This allowed us to gain a measure of whole Achilles tendon lengthening (strain) during movements including one-legged hopping, walking and running (Figure 3 & 2d). It is apparent that this tendon indeed acts like a classic energy storing spring and that high strains (up to 9%) can be achieved during hopping movements (Figure 3).

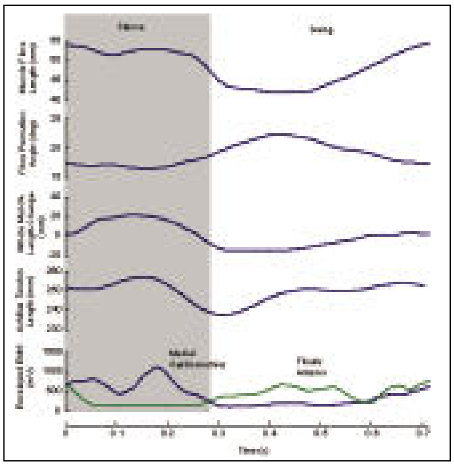

Figure 2: Example average results for one participant running at 10km/h on a flat treadmill. Measurements made with the ultrasound and motion analysis are: A) muscle fibre length, B) fibre pennation angle, C) whole muscle length, D) Achilles tendon length and E) muscle activity (EMG from the medial gastrocnemius and the antagonistic tibialis anterior).

This research is noteworthy because it suggests that the elastic tissues such as tendon and aponeurosis are responsible for high speed recoil of the MTC, thus making the muscle more efficient. In the future, these tools may invaluable in examining muscle dysfunction during locomotion.

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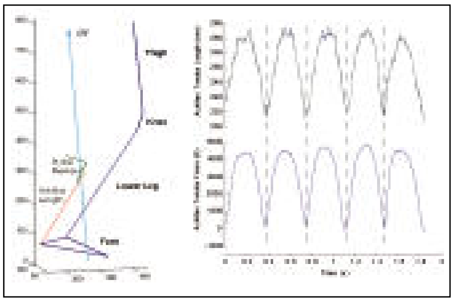

Figure 3: A) A stick figure representation of the measurements made during one-legged hopping. The Achilles tendon length was measured as the distance from the calcaneous marker to the projected ultrasound position of the muscle-tendon junction. Synchronous measurement of the ground reaction force (GRF) allowed for measurement of the Achilles tendon force. B) Achilles tendon length and force with respect to time during 5 consecutive one-legged hops on a force plate. The force and lengths are only plotted for the ground contact time, not the flight time. Achilles tendon length is also filtered with a 10Hz low pass filter to remove any high frequency noise due to the imaging technique (green line).

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