NASA Technical Memorandum 110412

Intramuscular Pressure Measurement During Locomotion in Humans

Richard E. Ballard

August 1996

National Aeronautics and
Space Administration

NASA Technical Memorandum 110412

Intramuscular Pressure Measurement During Locomotion in Humans

Richard E. Ballard, Ames Research Center, Moffett Field, California

August 1996

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRAMUSCULAR PRESSURE MEASUREMENT DURING LOCOMOTION IN HUMANS

RICHARD E. BALLARD

Ames Research Center

Summary

To assess the usefulness of intramuscular pressure (IMP) measurement for studying muscle function during gait, IMP was recorded in the soleus and tibialis anterior muscles of ten volunteers during treadmill walking and running using transducer-tipped catheters. Soleus IMP exhibited single peaks during late-stance phase of walking (181 ± 69 mmHg, mean ± S.E.) and running (269 ± 95 mmHg). Tibialis anterior IMP showed a biphasic response, with the largest peak (90 ± 15 mmHg during walking and 151 ± 25 mmHg during running) occurring shortly after heel strike. IMP magnitude increased with gait speed in both muscles. Linear regression of soleus IMP against ankle joint torque obtained by a dynamometer in two subjects produced linear relationships ($r = 0.97$). Application of these relationships to IMP data yielded estimated peak soleus moment contributions of 0.95 – 165 $\text{Nm} \cdot \text{kg}^{-1}$ during walking, and 1.43 – 2.70 $\text{Nm} \cdot \text{kg}^{-1}$ during running. IMP results from local muscle tissue deformations caused by muscle force development and thus, provides a direct, practical index of muscle function during locomotion in humans.

Introduction

Human locomotion involves a complex series of muscular interactions and coordinated movements. While the kinematics and dynamics of walking and running are well studied, no reliable method exists for measuring force production of individual muscles during locomotion in humans. Information on the forces produced by individual skeletal muscles during locomotion will improve our understanding of muscle physiology, musculoskeletal mechanics, neuromuscular coordination, and motor control. Such information may also aid development of exercise hardware and protocols for physical rehabilitation and training.

In the past, investigators have used mathematical modeling (refs. 4, 6, 21, and 31) and electromyography (EMG) (refs. 18, 19, 23, and 26) to estimate the contributions of individual muscles to joint moments during exercise. However, these indirect methods exhibit deficiencies related to the complex nature of human locomotion. With the aid of photography, force platforms, and mathematical models, much is known about the kinematics and dynamics of walking and running. However, because factors such as contraction velocity, muscle length, mode of contraction, muscle architecture and joint mechanics all affect individual muscle contraction force, mathematical models of individual muscles during dynamic activities are extremely complex and often inaccurate (refs. 5 and 21). Kinematic analyses of locomotion commonly describe actions of muscle groups, but moment contributions of individual muscles are difficult to discern.

While EMG patterns provide useful information about the phasic electrical activity of muscle, attempts to use EMG magnitude as an index of dynamic muscle contraction force have proved largely unsuccessful. Various disadvantages of this method exist, including nonlinear EMG/force calibration curves, fatigue-related changes, and low reproducibility (refs. 23, 24, and 26). While integrated or root mean square EMG is linearly related to individual muscle contraction force during isometric exercise in many muscles (refs. 13 and 18), this association is unreliable during dynamic activities which involve concentric and/or eccentric movements (refs. 1 and 22). Because the EMG/force relationship varies with mode and velocity of contraction, EMG is an unreliable index of muscle contraction force during locomotion.

Using a buckle transducer for recording tendon forces, a number of experiments have been performed to measure individual muscle forces in cats during dynamic activities (refs. 9, 11, and 29). This approach has also been applied to humans, with a buckle transducer surgically implanted around the Achilles tendon (ref. 17). While the buckle transducer is a valuable tool for measuring in vivo tendon tension in animals, inherent surgical risks, subject discomfort, and long recovery periods make it impractical for regular use. Furthermore, a buckle transducer on the Achilles tendon is unable to differentiate between individual contributions of the soleus and gastrocnemius to total tendon tension.

Intramuscular pressure (IMP), or fluid pressure within a muscle, increases linearly with individual muscle contraction force during isometric, concentric and eccentric activity (refs. 1, 16, 22, 24, and 25). IMP elevation results directly from increased muscle fiber tension, and therefore reflects the mechanical state within the muscle independent of muscle length and muscle activation. Thus, IMP may be used as a qualitative index of muscle contraction force: the higher the IMP the higher the force. Furthermore, calibration of IMP values with joint torque may provide quantitative estimates of individual muscle contraction force if the contraction force of that particular muscle can be isolated by a dynamometer.

The purpose of this investigation was to assess the usefulness of IMP measurement for studying soleus and tibialis anterior function during gait. These muscles are of particular interest because they are two of the primary muscles of the lower leg involved in locomotion, they are easily accessible by catheterization, and a substantial amount of soleus and tibialis anterior EMG and IMP data exists in the literature (refs. 1, 2, 4, 9, 14, 15, 20, 23, 25, 27, and 31). We hypothesized that transducer-tipped catheters would provide rapid and reproducible measures of IMP during walking and running, and that IMP would parallel muscle force production patterns predicted by kinematic analysis and tendon buckle transducer measurements.

We thank Dr. Alan Hargens, Dr. Donald Watenpaugh, Dr. Gregory Breit, and Gita Murthy, Dr. Leon Dorosz, Dr. Robert Whalen, Dr. Jorma Styf, David Chang, and Dr. Andrew Ertl for their scientific contributions; Karen Hutchinson for manuscript preparation; and our subjects for their interest and participation. This research was supported by NASA grants 199-14-12-04 and 199-26-12-38.

Methods

Subjects

Ten volunteers (age 20–48 years; weight 72 ± 13 kg, mean ± SD) participated in this investigation, after providing informed, written consent. All subjects were in good health as determined by comprehensive medical examination. Subjects refrained from caffeine, alcohol, medications, and strenuous exercise for 24 hours before study. The protocol was approved by the Human Research Institutional Review Board at NASA Ames Research Center.

Instrumentation

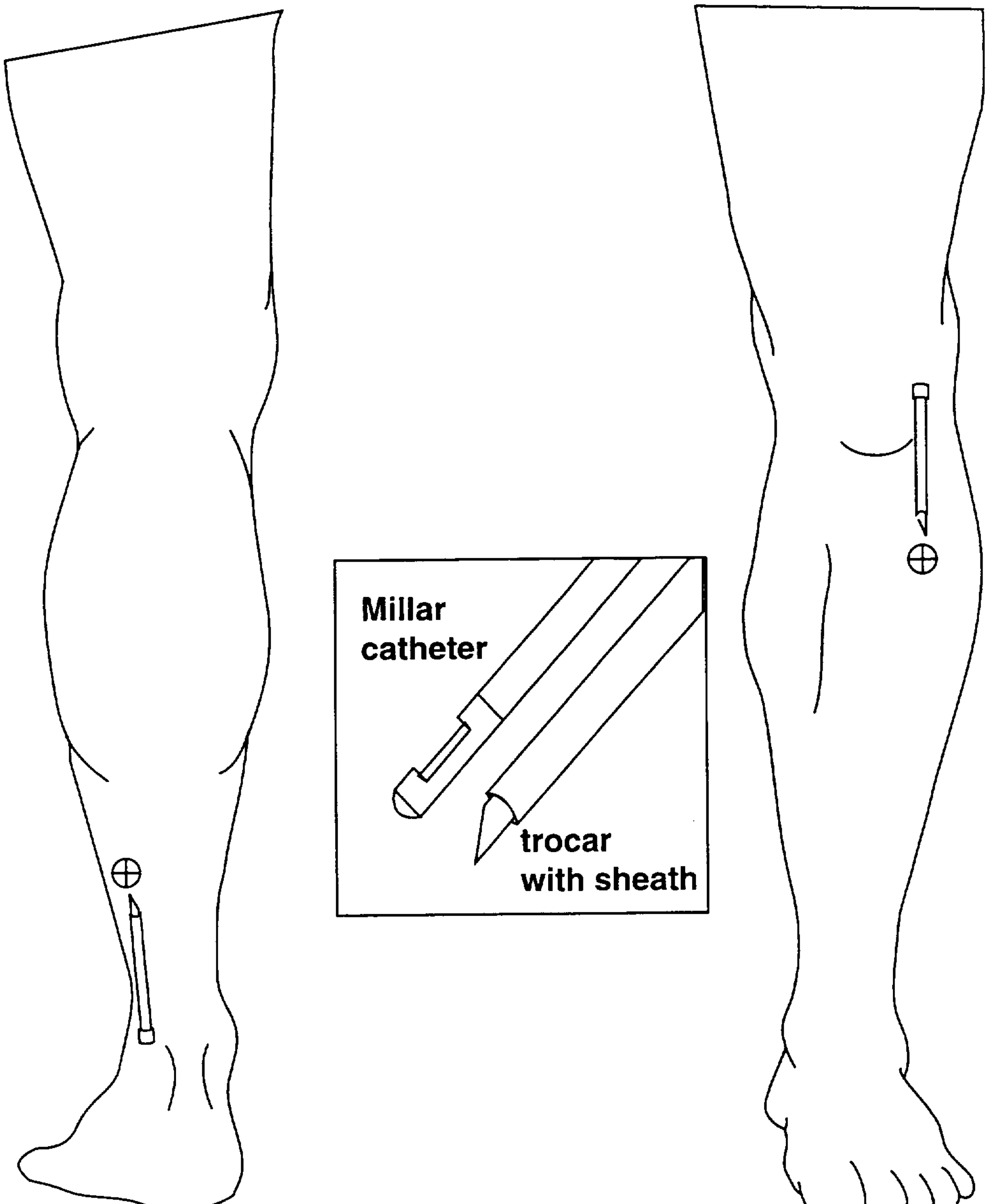
Intramuscular pressures were measured in the soleus and tibialis anterior muscles of the left leg during treadmill walking and running. Each insertion site was first shaved and cleaned with alcohol and Betadine iodine solution. The skin and muscle fascia were anesthetized with a 2–3 ml subcutaneous injection of 2 percent Lidocaine solution using a 5 cm 27-gauge needle. A 16–18 gauge catheter placement unit with a plastic sheath was then inserted into the muscle (proximally-directed for the soleus, distally-directed for the tibialis anterior) at an angle of approximately 25 deg to the skin surface. After penetration of the muscle fascia, the inner trocar was slightly withdrawn and the sheath was bluntly advanced in a direction parallel with the muscle fibers to a depth of approximately 2.5 cm from skin surface, or 5 cm from the insertion point. The inner needle was then removed and a 2–3 F transducer-tipped catheter (Millar Mikro-Tip, Houston, Tex.) was inserted through the sheath. Finally, the sheath was withdrawn from around the catheter, which was secured in place with sterile tape. Catheter function was confirmed by pressure pulses during palpation of skin above the catheter tip, and active plantarflexion and dorsiflexion of the ankle.

Catheter insertion site for the tibialis anterior was approximately 3 cm distal and 1 cm lateral to the tibial tuberosity (fig. 1). Soleus catheter insertion was on the posterolateral aspect of the leg one-third of the distance between the lateral malleolus and the lateral tibial condyle.

A force pad shoe insert (Electronic Quantification, Inc., Plymouth Meeting, Pa.) measured vertical ground reaction forces (GRF_Z) during treadmill walking and running. GRF_Z was used to identify stance and swing phases of the gait cycle for IMP comparisons. The pad was calibrated with a force plate (model OR6-5-1 Biomechanics Platform, Advanced Mechanical Technology, Newton, Mass.) prior to and following treadmill exercise.

Treadmill Gait Protocol (N = 10)

All subjects were familiarized with the protocol and practiced walking and running on a treadmill (Aerobics Inc., Little Falls, N.J.) prior to catheter insertion. Self-selected walking and running speeds for each subject were determined during this familiarization. Self selected walking speed averaged 1.3 ± 0.3 m · sec^{-1}, while self-selected running speed averaged 2.8 ± 0.6 m · sec^{-1}.



Soleus

Tibialis anterior

Figure 1. Catheter insertion sites. Soleus catheter is inserted at the posterolateral aspect of the leg, one-third of the distance from lateral malleolus to lateral tibial condyle. Tibialis anterior catheter is inserted 3 cm distal and 1 cm lateral to the tibial tuberosity. The recessed sensor at the tip of the Millar catheter is directed towards the skin.

After catheter insertion, intramuscular pressures in the soleus and tibialis anterior were measured following 30 sec of recumbency and 30 sec of quiet standing. After these baseline measurements were taken, subjects walked on the treadmill at their pre-selected walking speed. Data collection began after at least 30 sec of walking. IMP and GRF_Z data were recorded for 15 sec (minimum of 10 step cycles) at a rate of 100 Hz using an IBM-compatible 486 computer with Labtech Notebook software (Labtech, Wilmington, Mass.) and a data acquisition board (Metrabyte DAS 20, Taunton, Mass.). Treadmill speed was then increased to the pre-selected running speed for at least 30 sec before 15 sec of running data were recorded. Each subject performed a total of 3 walking/running trials with at least 1 minute between trials, during which time 15 sec of data were collected during quiet standing to re-establish baseline conditions.

Calibration of IMP (N = 2)

To convert IMP values into estimated moment contributions of the soleus during walking and running, two of the subjects also performed plantarflexion and dorsiflexion exercises using a Lido Active isokinetic dynamometer (Loredan Biomedical, Davis, Calif.) prior to treadmill exercise. Isometric, concentric, and eccentric contractions were performed. Subjects were positioned and secured with the left knee and hip joints flexed at 90 deg, thus minimizing contributions of the gastrocnemius to soleus contractions (refs. 1 and 27). Subjects wore their own athletic shoes, and the left foot was secured to the Lido footplate by two Velcro straps. Ankle neutral position was defined as a 90 deg angle between foot and tibia. Limits of ankle range of motion were then determined by passive plantar- and dorsiflexion of the ankle joint. Isometric contractions were performed at five different joint angles (spaced by approximately 10 deg) covering the entire range of motion. Concentric isokinetic contractions were performed at 60, 120, and 240 deg $\cdot$ sec^{-1}. Eccentric isokinetic contractions were performed at 30, 60, and 120 deg $\cdot$ sec^{-1}. At each joint angle (in the case of isometric contractions) or velocity (for concentric and eccentric contractions), subjects performed at least four contractions of intensity approximating 100, 75, 50, and 25 percent of maximal voluntary effort. Subjects rested for approximately 3 min between each mode of contraction. During each set of contractions, IMP, footplate velocity and ankle joint torque and angle were continuously recorded at a rate of 100 Hz.

Following a brief rest period, the two subjects then performed treadmill exercise at self-selected speeds as previously described. To determine the effect of locomotion speed on soleus IMP and estimated torque, these subjects also performed 15 sec of walking and running at the following speeds: 0.75, 1.25, 1.75 m $\cdot$ sec^{-1} for walking and 1.75, 3.0, 4.0 m $\cdot$ sec^{-1} for running.

Data Analysis

Data were normalized to represent 0 (heel strike) to 100 percent of each step cycle. A spline interpolation was performed on each data set. Interpolated data were then re-sampled at 1 percent intervals to synchronize data points within and across subjects. For each subject, representative traces (showing soleus and tibialis anterior IMP patterns) were produced by calculating means across four step cycles at 1 percent increments of the cycle. Positions of peak IMP with respect to the normalized gait cycle were recorded, and means (± S.E.) across subjects were calculated. Paired t-tests identified statistically significant differences between IMP peaks at $\alpha = 0.05$.

For each of the two subjects who underwent isometric and isokinetic calibration procedures prior to treadmill exercise, IMP, and ankle joint torque for each contraction were plotted, and linear regression analyses were performed. The resulting linear equations were later used to convert soleus IMP data obtained during walking and running into estimates of moment contributions from the soleus.

Results

Soleus and tibialis anterior IMP from one representative subject are illustrated in figure 2. IMPs within each subject were quite uniform (maximum intrasubject S.D. equaled 10 mmHg for soleus and 8 mmHg for the tibialis anterior), despite relatively larger variability between subjects in IMP magnitude.

In all subjects, soleus IMP closely paralleled ground reaction force during the late stance phase of gait, with single peaks during walking (181 ± 22 mmHg at 53 ± 1 percent of gait cycle, mean ± S.E.) and running (269 ± 30 mmHg at 20 ± 1 percent) (fig. 3). IMP patterns in the tibialis anterior were somewhat more variable, but consistently showed a biphasic response during both walking and running. During walking, the first peak (90 ± 15 mmHg) occurred shortly after heel strike (6 ± 1 percent), and the second peak was smaller in amplitude (67 ± 11 mmHg) and occurred near toe-off (48 ± 0 percent). The same pattern was evident during running, with the first tibialis anterior IMP peak averaging 151 ± 25 mmHg (at 3 ± 0 percent of gait cycle) and the second, smaller peak averaging 109 ± 21 mmHg (at 19 ± 1 percent of gait cycle). Average peak intramuscular pressures during rest and treadmill exercise are given in the table 1.

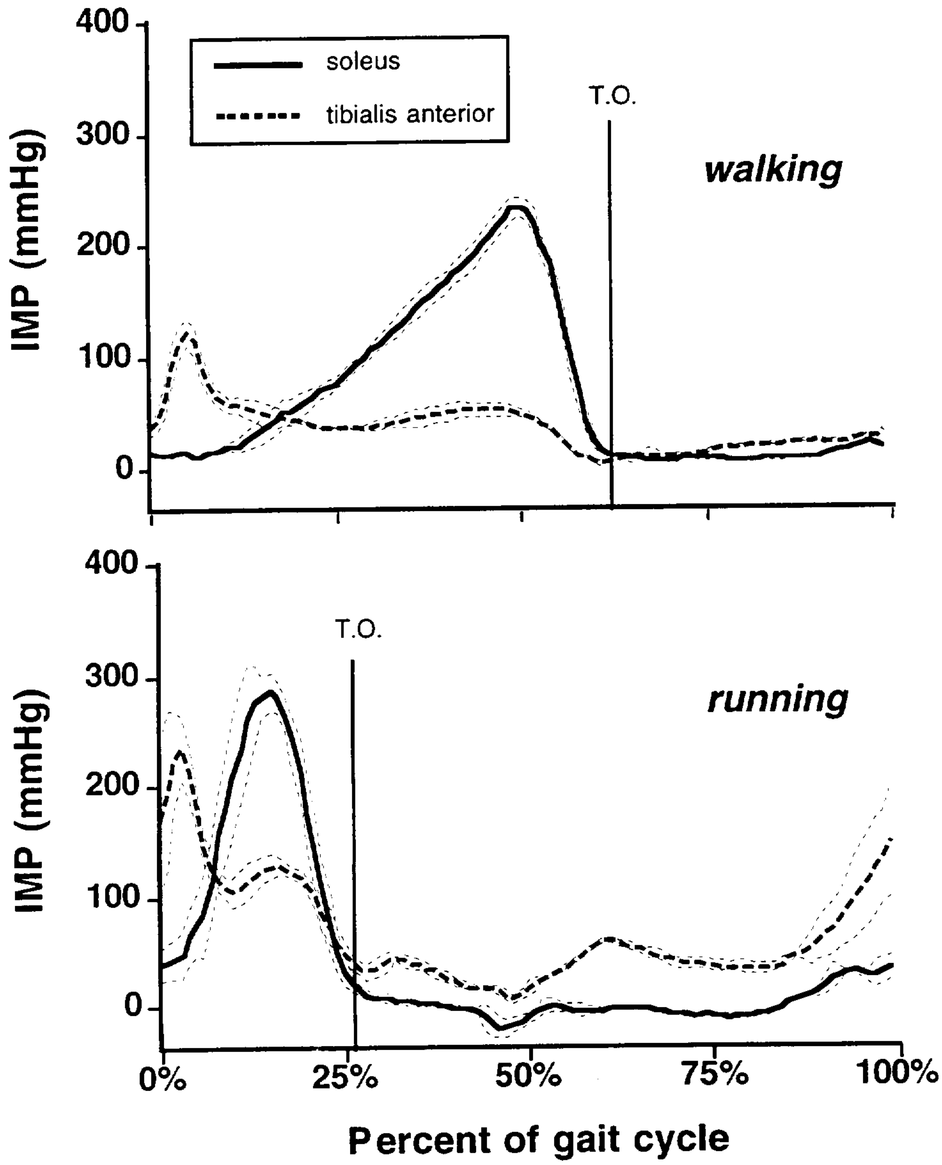


Figure 2. Soleus (solid) and tibialis anterior (dashed) intramuscular pressures in one representative subject during walking (top) and running (bottom). Each trace represents a mean of four step cycles, sampled at 1% intervals. Thin dashed lines represent standard deviations over the four cycles. T.O. = toe-off.

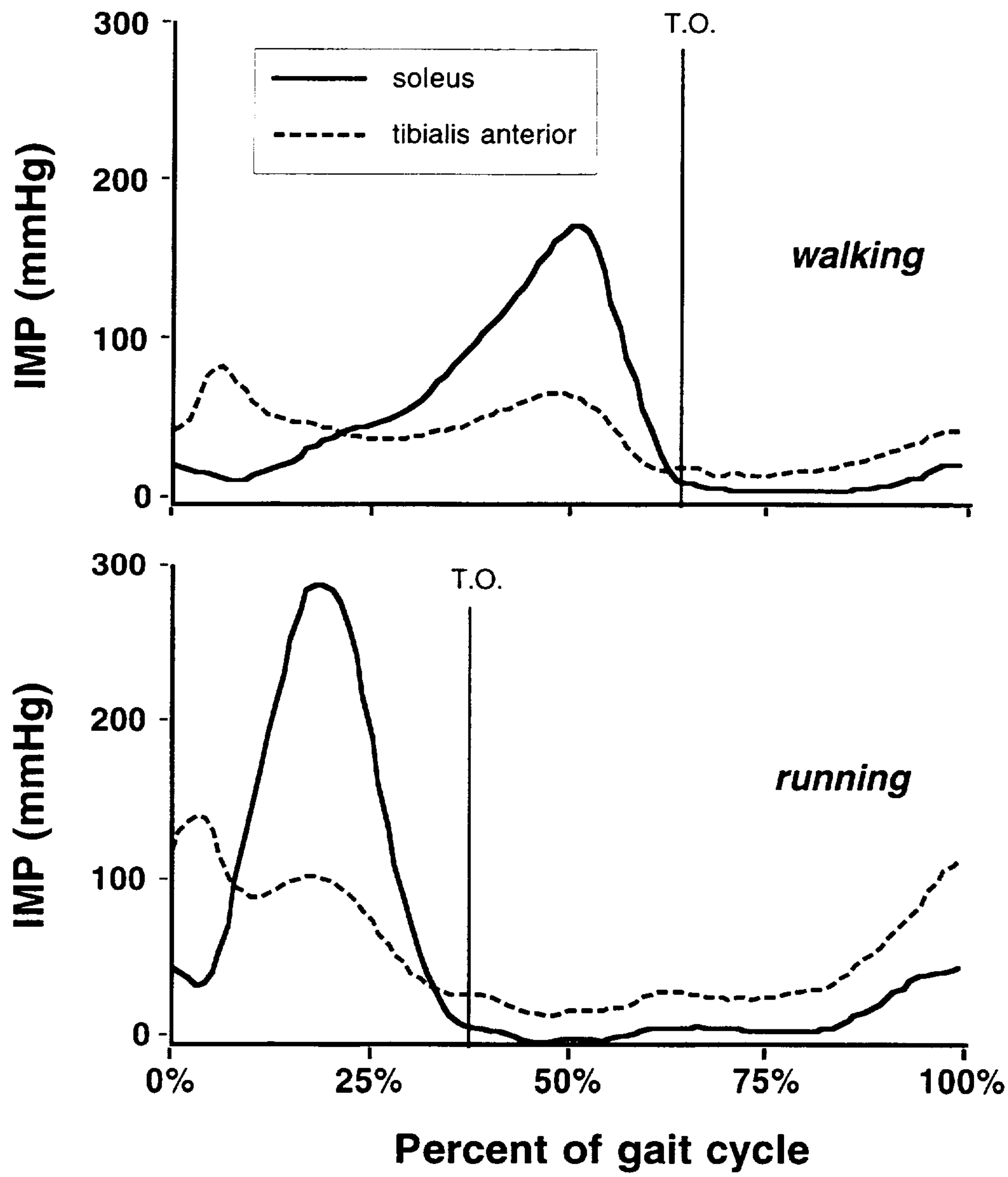


Figure 3. Soleus (solid) and tibialis anterior (dashed) intramuscular pressures during walking (top) and running (bottom) averaged across all subjects (N = 10). Walking speed averaged 1.3 ± 0.3 m • sec^{-1}; running speed averaged 2.8 ± 0.6 m • sec^{-1}. T.O. = toe-off.

Table 1. Peak intramuscular pressures and corresponding positions in the step cycle. Data represent means ± SE (N = 10). Walking speed averaged 1.3 ± 0.3 m · sec^{-1}; running speed averaged 2.8 ± 0.6 m · sec^{-1}

	Soleus		Tibialis anterior Peak 1		Tibialis anterior Peak 2	
Condition	IMP, mmHg	Position, % of cycle	IMP, mmHg	Position, % of cycle	IMP, mmHg	Position, % of cycle
Supine	8 ± 1	----	11 ± 1	----	----	----
Standing	37 ± 5	----	35 ± 3	----	----	----
Walking	181 ± 22	53 ± 1	90 ± 15†	6 ± 1	67 ± 11	48 ± 0
Running	269 ± 30*	20 ± 1*	150 ± 25*†	3 ± 0	109 ± 21*	19 ± 1*

* = Different than walking; † = greater than peak 2 ($p < 0.05$).

In the two subjects who performed dynamometric calibrations prior to treadmill exercise, linear regression of IMP versus ankle joint torque produced the following relationships (fig. 4): IMP = 2.53(torque) + 0.29 [r = 0.97], and IMP = 1.45(torque) + 0.71 [r = 0.97]. Application of these relationships to IMP data during gait yielded estimated peak soleus moment contributions of 0.96 – 1.40 Nm · kg^{-1} (subject A) and 0.95 – 1.65 Nm · kg^{-1} (subject B) during walking, and 1.43 – 1.68 Nm · kg^{-1} (subject A) and 1.93 – 2.70 Nm · kg^{-1} (subject B) during running (fig. 5). In both subjects, peak IMP increased with gait speed.

None of the subjects reported undue discomfort due to catheter placement or exercise. In two subjects, reliable IMP data from the tibialis anterior were not obtained due to catheter movement or malfunction.

Discussion

These results demonstrate that patterns of intramuscular pressure development in the soleus and tibialis anterior during walking and running are similar to patterns of estimated ankle joint moments (refs. 10, 21, and 31), Achilles tendon tension measured with a buckle transducer (ref. 17), and qualitative patterns of phasic EMG activation (refs. 2 and 31) (fig. 6). The soleus exerts a single peak in IMP near push off, when the ankle joint is undergoing active plantarflexion. Pressure patterns in the tibialis anterior during walking and running are biphasic in nature. The first peak occurs near heel strike as the tibialis anterior is actively contracting to stabilize the ankle joint. The second peak, significantly smaller in amplitude than the first, occurs near the end of the stance phase as the tibialis anterior is eccentrically activated to help stabilize the ankle joint during push-off. Although significant, the difference in magnitude between the two tibialis anterior IMP peaks is not as dramatic as published EMG activation patterns might suggest (ref. 31) (fig. 6). For example, the tibialis anterior EMG trace in figure 6 shows only a small peak at walking push-off (approximately 15 percent as great as the peak which occurs at heel strike), and a relatively large peak as the foot is dorsiflexed during the swing phase (at about 75 percent of gait cycle). Because the tibialis anterior is eccentrically co-activated during the push-off phase of the step cycle, and eccentric contractions are known to generate more force per unit EMG (ref. 27), it is likely that actual tension in the muscle exceeds tension estimated by EMG.

While qualitative patterns of IMP development during locomotion agree generally with phasic EMG activity, the utility of IMP measurement lies in the magnitudes of pressure (ref. 1). Because IMP is a physical property related to force development in a muscle, fluid pressure in a muscle increases linearly with increasing tension, apparently regardless of contraction velocity, joint angle, and mode of contraction (fig. 4), all of which continuously change during dynamic activities. Consider the soleus, for example: at heel strike and through the beginning of the stance phase, the soleus is eccentrically activated (being lengthened during a contraction effort). As the stance phase progresses, the soleus actively contracts and eventually shortens, helping to propel the body forward. Variations in muscle length, contraction mode, and contraction velocity during dynamic activities are major reasons why EMG is unreliable for determining contraction force of individual muscles. Intramuscular pressure, however, appears to be directly and linearly related to contraction force regardless of these factors. Thus if IMP increases, then it can be assumed that tension in the muscle increases proportionately.

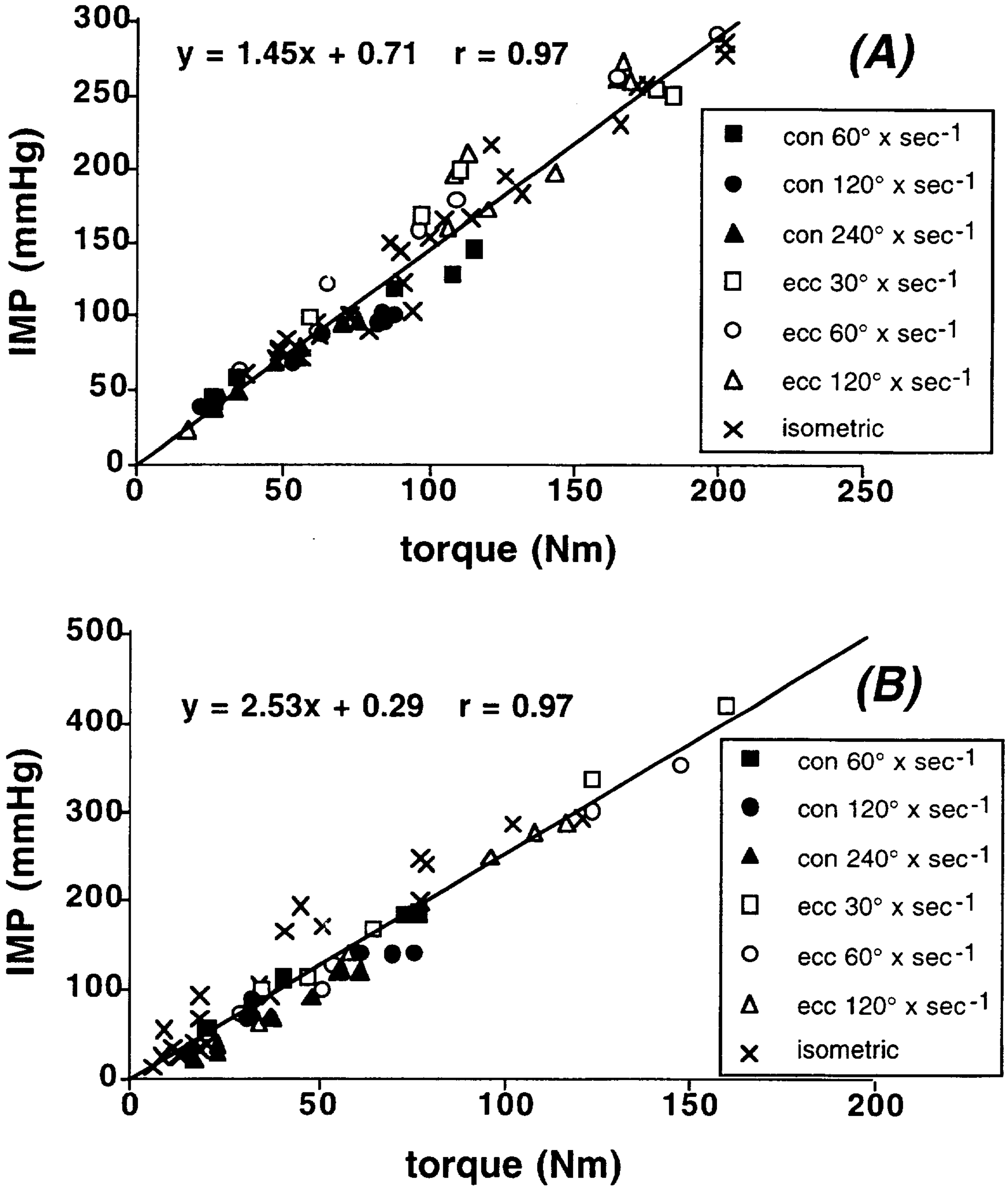


Figure 4. Dynamometric calibration of soleus IMP with torque during isometric, concentric, and eccentric contractions in two subjects (subject A, top; subject B, bottom). Each point represents peak IMP and torque of a single contraction. Linear regression equations were later used to convert IMP values obtained during locomotion into moment contributions of the soleus. "con" = concentric; "ecc" = eccentric.

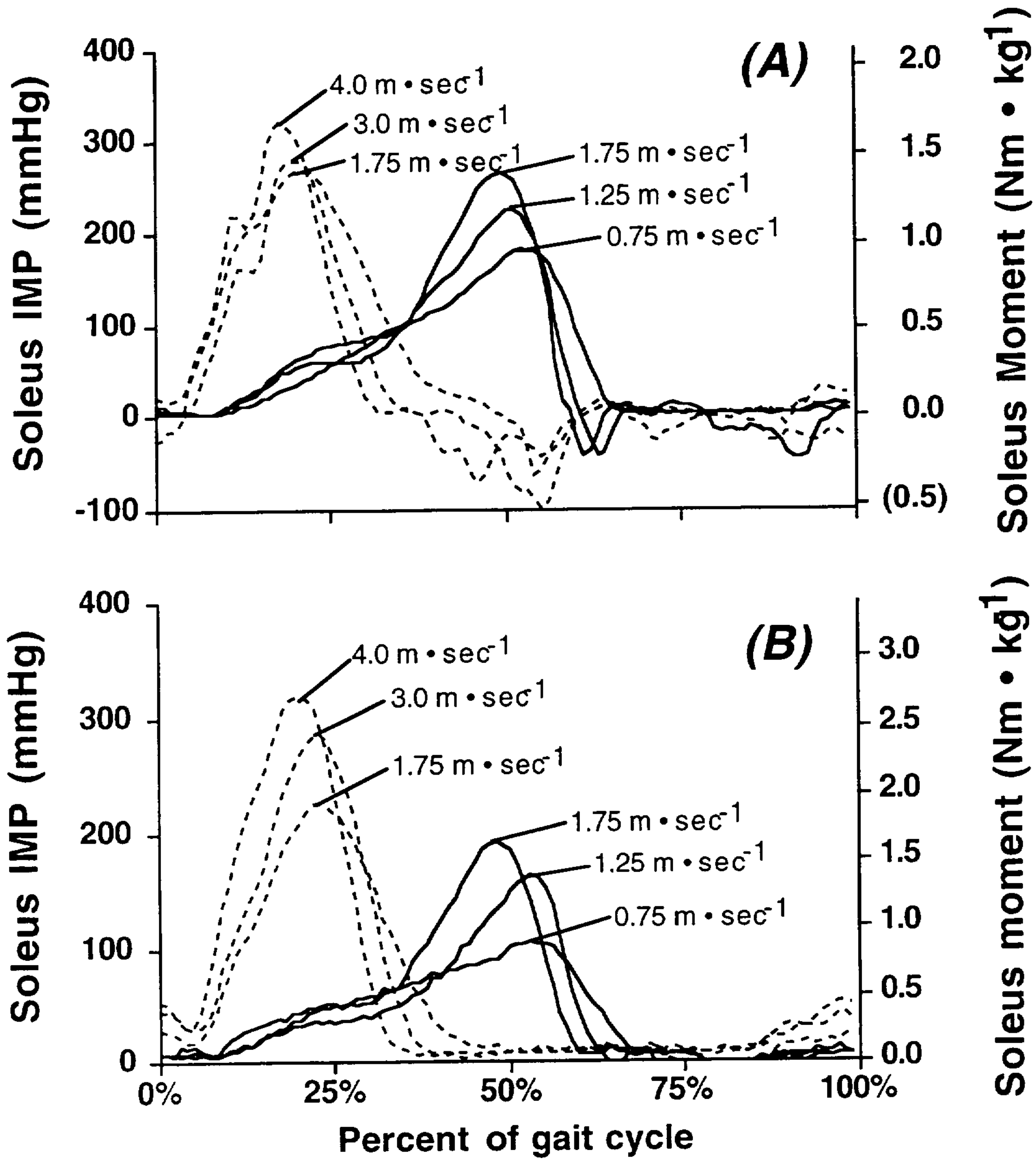


Figure 5. Effect of locomotion speed on IMP and moment contributions of the soleus (subject A, top; subject B, bottom). Moment values were derived using regression equations from figure 4. In both subjects, peak intramuscular pressure increased with speed of walking (solid lines) and running (dashed lines).

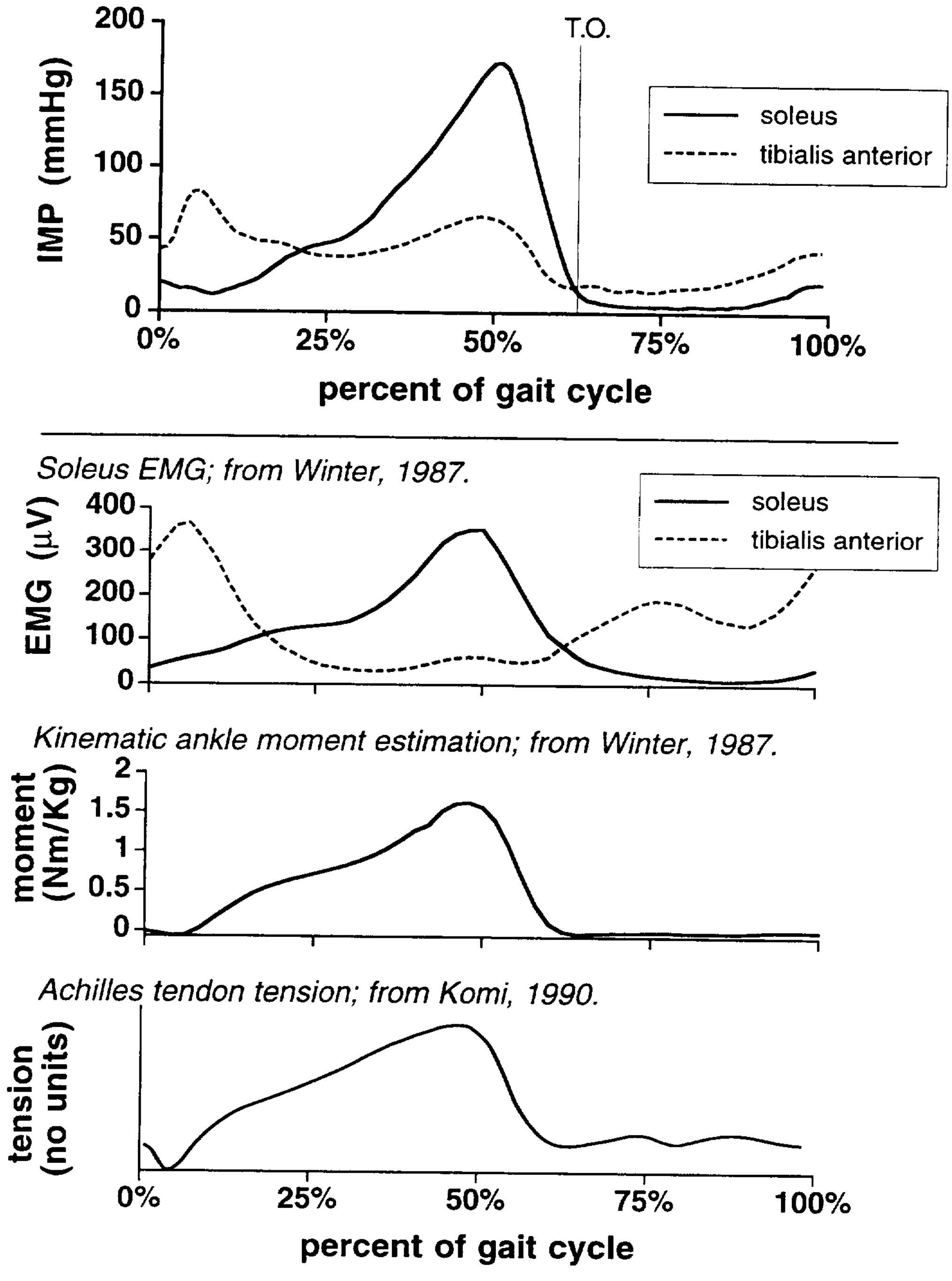


Figure 6. Comparison of IMP from present study (top, N=10) with qualitative patterns of EMG activity (using surface electrodes, from Winter, 1987), ankle joint moment (using joint kinematics, from Winter, 1987), and Achilles tendon tension (using a buckle transducer, from Komi, 1990) during walking.

Application of IMP/torque regression equations to the IMP data collected in the present study yields estimated soleus moment contributions of 1.18 and 1.39 $Nm \cdot kg^{-1}$ (subject A and B, respectively) during normal (1.25 $m \cdot sec^{-1}$) walking. While other plantar flexors, particularly the gastrocnemius, are known to contribute to plantarflexion torque during walking, the soleus is the dominant contributor. Therefore, estimated moment contributions of the soleus presented here agree quite will with those of Winter (ref. 31), Groh and Baumann (ref. 10), and Cappozzo and co-workers (ref. 5), who reported combined plantarflexor torques during walking of 1.5 – 2.4 $Nm \cdot kg^{-1}$.

IMP peaks in the soleus and tibialis anterior were higher in all subjects during running than walking (table 1), indicating increased muscle tension during the stance phase of running. Furthermore, in the two subjects who exercised at multiple speeds of both walking and running, estimated moment contributions of the soleus increased with each increase in treadmill speed. Kirby and co-workers (ref. 15) reported similar increases in peak tibialis anterior IMP with increased speed of locomotion.

Our findings disagree with reports that soleus tension in cats, as measured by tendon buckle transducers, does not increase with locomotion speed (refs. 9, 11, and 29). Various factors may contribute to this discrepancy. First, there are probably inherent differences between humans and cats (and likely between individuals) with respect to relative contributions of different muscles during gait. Second, walking speeds used in our study were relatively slow; it is possible that as maximal walking speeds are approached, contribution of the soleus to ankle joint torque levels off while the gastrocnemius contribution increases. Finally, contraction of the gastrocnemius during gait may compress the soleus, resulting in additional increases in soleus IMP which were not observed during dynamometric calibration trials (as the knee and hip joints were held at 90 deg of flexion).

Our investigation is not the first to measure IMP during locomotion in humans. IMP in the tibialis anterior (refs. 14 and 15) and vastus lateralis (ref. 7) has been measured during locomotion. However, the primary focus of those studies was the effect of IMP on muscle perfusion (compartment syndrome) and exercise-induced tissue damage. Baumann and co-workers (ref. 3) measured gastrocnemius IMP during walking, but their data were limited by the use of fluid-filled wick catheter systems, which have characteristically slow response times and hydrostatic motion artifacts (refs. 8 and 24). Sutherland and co-workers (ref. 28) later measured gastrocnemius IMP using a fiber-optic Camino catheter, which provides a five-fold frequency response improvement over fluid-filled systems, but is approximately three times as large and thus uncomfortable during exercise (ref. 8). Electronic transducer-tipped catheters used in the present study have similar frequency response characteristics, but they are smaller, they are more flexible, and they have a recessed sensor which eliminates the need for the rigid fluid-filled sheath required by Camino catheters.

While the transducer-tipped catheters used in this investigation generally performed well, negative IMP spikes were sometimes evident during muscle activity immediately following insertion. These spikes usually disappeared following 1–3 min of palpation and muscle contraction, probably as interstitial fluid filled the space above the sensor surface. In a few instances, however, negative spikes persisted during exercise (fig. 5(a)). Negative relaxation pressures have been reported previously (ref. 8), and may result from slight movement of the catheter during contraction or location of the catheter tip in muscle tissue close to bone. Alternatively, one might hypothesize that low relaxation pressures are physiological, and function to aid muscle perfusion following contraction.

It should be noted that the slope of the IMP/force relationship, while linear, varies both within and between muscles (refs. 12, 13, 24, and 25). Variations between muscles depend upon muscle thickness, fiber curvature, pennation angle, and other factors related to muscle architecture. Within a muscle, pressure increases with depth (ref. 24). Repeated catheterizations of the same muscle may show slight differences in baseline pressure and magnitude of pressure response due to variations in positioning of the pressure sensor. When measured in a single location, however, IMP responses to muscle contraction are highly reproducible (ref. 24). It is therefore important to ensure that the transducer is in the same position during IMP/torque calibrations as dynamic exercise testing.

During dynamometric calibrations, total torque measured by the dynamometer was probably affected both agonistically and antagonistically by other muscles in the foot and lower leg. While holding the knee and hip joints at 90 deg of flexion during dynamometry helped maximize soleus contribution to plantarflexion torques (refs. 1 and 27), the net effect of surrounding muscles is unknown. Therefore the linear regression equations of IMP versus ankle joint torque provide only estimates of soleus moment contributions. Because of the difficulty in isolating forces produced by individual muscles, in vivo calibration of IMP values with torque or force may not be possible in all muscles. Lack of an accurate standard against which to compare IMP-derived moment contributions further illustrates the need for a reliable, reproducible method of monitoring contraction force of specific muscles in vivo.

These results support the use of IMP measurement to assess function of individual muscles during locomotion in humans. Because IMP magnitude is directly related to muscle force output, measurement of IMP during dynamic exercise provides a valuable index of individual muscle force during locomotion and other dynamic activities.

References

1. Aratow, M.; Ballard, R. E.; Crenshaw, A. G.; Styf, J.; Watenpaugh, D. E.; Kahan, N. J.; and Hargens, A. R.: Intramuscular Pressure and Electromyography as Indexes of Force During Isokinetic Exercise. J. Appl. Physiol., vol. 74 , 1993, pp. 2634–2640.

2. Basmajian, J.; and De Luca, C.: Muscles Alive: Their Functions Revealed by Electromyography, 5th ed. Maryland: Williams & Wilkins., 1985, pp. 374–377, 379.

3. Baumann, J. U.; Sutherland, D. H.; and Hanggi, A.: Intramuscular Pressure During Walking. Clin. Orthop. Rel. Res., vol. 145, 1979, pp. 292–299.

4. Bobbert, M. F.; and van Ingen Schenau, G. J.: Isokinetic Plantar Flexion: Experimental Results and Model Calculations. J. Biomechanics, vol. 23, 1990, pp. 105–119.

5. Cappozzo, A.; Leo, T.; and Pedotti, A.: A General Computing Method for the Analysis of Human Locomotion. J. Biomechanics, vol. 8, 1975, pp. 307–320.

6. Cappozzo, A.; Figura, F.; Marchetti, M.; and Pedotti, A.: The interplay of muscular and external forces in human ambulation. J. Biomechanics, vol. 9, 1976, pp. 35–43.

7. Crenshaw, A. G.; Karlsson, S.; Styf, J.; Bäcklund, T.; and Fridén, J.: Knee Extension Torque and Intramuscular Pressure of the Vastus Lateralis Muscle During Eccentric and Concentric Activities. Eur. J. Appl. Physiol., vol. 70, 1995, pp. 13–19.

8. Crenshaw, A. G.; Styf, J. R.; and Hargens, A. R.: Intramuscular Pressures During Exercise: An Evaluation of a Fiber Optic Transducer-Tipped Catheter System. Eur. J. Appl. Physiol., vol. 65, 1992, pp. 178–182.

9. Gregor, R. J.; Roy, R. R.; Whiting, W. C.; Lovely, R. G.; Hodgson, J. A.; and Edgerton, V. R.: Mechanical Output of the Cat Soleus During Treadmill Locomotion: In vivo vs in situ characteristics. J. Biomechanics, vol. 21, 1988, pp. 721–732.

10. Groh, H.; and Baumann, W.: Joint and Muscle Forces Acting in the Leg During Gait. In: Biomechanics, vol. 5A, edited by P.V. Komi. Baltimore: University Park Press, 1976, pp. 328–333.

11. Herzog, W.; and Leonard, T. R.: Leonard. Validation of Optimization Models that Estimate the Forces Exerted by Synergistic Muscles. J. Biomechanics, vol. 24, 1991, pp. 31–39.

12. Hill, A. V.: The Pressure Developed in Muscle During a Contraction. J. Physiol., vol. 107, 1948, pp. 518–526.

13. Järvholm, U.; Palmerud, G.; Karlsson, D.; Herberts, P.; and Kadefors, R.: Intramuscular Pressure and Electromyography in Four Shoulder Muscles. J. Orthop. Res., vol. 9, 1991, pp. 609–619.

14. Kirby, R. L.; and McDermott, A. G. P.: Anterior Tibial Compartment Pressures During Running with Rearfoot and Forefoot Landing Styles. Arch. Phys. Med. Rehabil., vol. 64, 1983, pp. 296–299.

15. Kirby, R. L.; Marlow, R. W.; MacLeod, D. A.; and Marble, A. E.: The Effect of Locomotion Speed on the Anterior Tibial Intramuscular Pressure of Normal Humans. J. Biomechanics, vol. 21, 1988, pp. 357–360.

16. Körner, L.; Parker, P.; Alstrom, C.; Andersson, G. B. J.; Herberts, P.; Kadefors, R.; Palmerud, G.; and Zetterberg, C.: Relation of Intramuscular Pressure to the Force Output and Myoelectric Signal of Skeletal Muscle. J. Orthop. Res., vol. 2, 1984, pp. 289–296.

17. Komi, P. V.: Relevance of In Vivo Force Measurements to Human Miomechanics. J. Biomechanics, vol. 23, 1990, pp. 23–34.

18. Komi, P. V.: Relationship Between Muscle Tension, EMG and Velocity of Contraction Under Concentric and Eccentric Work. In: New Developments in Electromyography and Clinical Neurophysiology, edited by J. E. Desmedt. Basel: Karger, vol. 1, 1973, pp. 596–606.

19. Lawrence, J. H.; and De Luca, C. J.: Myoelectric Signal Versus Force Relationship in Different Human Muscles. J. Appl. Physiol., vol. 54, 1983, pp. 1653–1659.

20. Murthy, G.; Watenpaugh, D. E.; Ballard, R. E.; and Hargens, A. R.: Supine Exercise During Lower Body Negative Pressure Effectively Simulates Upright Exercise in Normal Gravity. J. Appl. Physiol., vol. 76, 1994, pp. 2742–2748.

21. Olney, S. J.; and Winter, D. A.: Predictions of Knee and Ankle Moments of Force in Walking from EMG and Kinematic Data. J. Biomechanics, vol. 18, 1985, pp. 9–20.

22. Parker, P.; Körner, L.; and Kadefors, R.: Estimation of Muscle Force from Intramuscular Total Pressure. Med. Biol. Eng. Comput., vol. 22, 1984, pp. 453–457.

23. Perry, J.; and Beckey, G. A.: EMG-Force Relationships in Skeletal Muscle. In: CRC Critical Reviews in Biomedical Engineering. Boston, Mass.: CRC, 1981, pp. 1–22.

24. Sejersted, O. M.; Hargens, A. R.; Kardel, K. R.; Blom, P.; Jensen, O.; and Hermansen, L.: Intramuscular Fluid Pressure During Isometric Contraction of Human Skeletal Muscle. J. Appl. Physiol., vol. 56, 1984, pp. 287–295.

25. Sejersted, O. M.; and Argens, A. R.: Intramuscular Pressures for Monitoring Different Tasks and Muscle Conditions. In: Motor Control VII. edited by D. G. Stuart et al. Tucson, Ariz.: Motor Control Press, 1995, pp. 339–350.

26. Solomonow, M.; Baratta, R.; Zhou, B. H.; Shoji, H.; and D'Ambrosia, R.: Historical Update and New Developments on the EMG-Force Relationships of Skeletal Muscles. Orthopaedics, vol. 9, 1986, pp. 1541–1543.

27. Styf J.; Aratow, M.; Ballard, R. E.; Crenshaw, A. G.; Watenpaugh, D. E.; and Hargens, A. R.: Intramuscular Pressures and Torque During Isometric, Concentric, and Eccentric Muscular Activity. Scand. J. Med. Sci. Sports, vol. 5, 1995, pp. 291–296.

28. Sutherland, D. H.; Bowler, J. R.; Focht, L. M.; and Wyatt, M. P.: Dynamic Intramuscular Pressure and EMG in Normal Adult Gastrocnemius. Transactions of the 35th Annual Meeting of the Orthopaedic Research Society, vol. 14, 1989, p. 319.

29. Walmsey, B.; Hodgson, J. A.; and Burke, R. E.: Forces Produced by Medial Gastrocnemius and Soleus Muscles During Locomotion in Freely Moving Cats. J. Neurophysiol., vol. 41, 1978, pp. 1203–1216.

30. Winter, D. A.: Moments of Force and Mechanical Power in Jogging. J. Biomechanics, vol. 16, 1983, pp. 91–97.

31. Winter, D. A.: The Biomechanics and Motor Control of Human Gait. Waterloo, Ontario: University of Waterloo Press, 1987, 72 p.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1996

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Intramuscular Pressure Measurement During Locomotion in Humans

5. FUNDING NUMBERS
199-14-12-04
199-26-12-38

6. AUTHOR(S)
Richard E. Ballard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
A-962341

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-110412

11. SUPPLEMENTARY NOTES
Point of Contact: Richard E. Ballard, Ames Research Center, MS 239-11,
Moffett Field, CA 94035-1000; (415) 604-5747

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category –51

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

To assess the usefulness of intramuscular pressure (IMP) measurement for studying muscle function during gait, IMP was recorded in the soleus and tibialis anterior muscles of ten volunteers during treadmill walking and running using transducer-tipped catheters. Soleus IMP exhibited single peaks during late-stance phase of walking (181 ± 69 mmHg, mean ±S.E.) and running (269 ± 95 mmHg). Tibialis anterior IMP showed a biphasic response, with the largest peak (90 ± 15 mmHg during walking and 151 ± 25 mmHg during running) occurring shortly after heel strike. IMP magnitude increased with gait speed in both muscles. Linear regression of soleus IMP against ankle joint torque obtained by a dynamometer in two subjects produced linear relationships ($r = 0.97$). Application of these relationships to IMP data yielded estimated peak soleus moment contributions of 0.95 – 165 Nm ·kg–1 during walking, and 1.43 – 2.70 Nm ·kg–1 during running. IMP results from local muscle tissue deformations caused by muscle force development and thus, provides a direct, practical index of muscle function during locomotion in humans.

14. SUBJECT TERMS
Muscle force, Soleus, Tibialis Anterior

15. NUMBER OF PAGES
18

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		