Impacts of Augmented Running on Energy Expenditure and Leg Muscle Activity

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Abstract: This study analyzes the impacts of a passive exotendon on human running economy for flat declined, and inclined paths. It consists of two portions, outdoor and indoor experiments. Outdoor experiments include two trials, one trial being a natural run followed by an exotendon run on varying inclines. Net heart rate, step cadence, and step length data is recorded. Indoor experiments encompass two trials, one trial being two consecutive natural and exotendon runs. These are conducted on a flat treadmill. Electromyographic (EMG) and ground reaction force data are recorded. Our findings show improvements in both decline and flat iterations while incline benefits are limited. Greater benefits are seen in 60 N m^{-1} iterations. Variability in outdoor conditions influenced outcomes in initial experiments. Further research with greater sample sizes and variable indoor steepness is recommended to further validate findings on various steepness grades.

1. Introduction

Running as a form of locomotion for humans has long been seen as inefficient. Only every 10 in 100 calories burned is used to do useful work on the environment. Most energy is spent in the stance phase of running supporting body weight and redirecting the center of mass, with a small amount reserved for leg swing. This study seeks to replicate passive elastic-like tendons seen in many animals. Recent studies have analyzed the application of an "exotendon," an elastic resistance band connected to the ankles which stores and returns expended energy during running cycles.

While studies show improvement in running economy of around 6.4% [1], their experiments are only conducted on indoor treadmills. This specific study seeks to test the applicability of an exotendon on various steepness grades outdoors, while using indoor testing for validation. It additionally investigates the impacts of varying resistant strengths for exotendons.

Due to practical challenges in outdoor testing, respiratory gas, ground force sensor, and electromyographic (EMG) analysis is replaced with net heart rate analysis. This data, when paired with subject body weight is a reliable alternative for measuring overall energy expenditure [4]. To validate this alternate measuring technique used in outdoor experiments, indoor testing with electromyograms of 8 major leg muscles and ground reaction forces were recorded and analyzed.

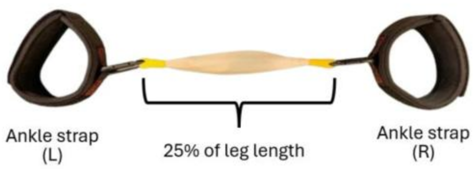

Fig. 1: Exotendon

We hypothesize that while flat improvements are consistently seen, there will be less improvement on sloped surfaces, either inclined or declined. This may be because moments applied by the exotendon, when paired with the effects of gravity on sloped surfaces, could increase the necessary force required by subjects to complete the same work.

2. Materials and Methods

2.1 Subjects

Of the 5 total subjects, all participated in the indoor experiments while only 2 participated in outdoor experimentation. They are all healthy males with no known musculoskeletal issues (age: 23.4 ± 1.7; height: 175.8 ± 7.5 cm; mass: 69.4 ± 8.2 kg).

2.2 Equipment

During outdoor experiments, the equipment used consisted of a fitness watch (Forerunner 935, Garmin Ltd., USA), a device to measure advanced running metrics (Running Dynamics Pod, Garmin Ltd., USA) and a heart rate monitor (HRM-Tri, Garmin Ltd., USA).

During indoor experiments, the equipment consisted of a treadmill with ground reaction force sensors (ITR5018, Bertec Corporation, USA), electromyographic sensors (PicoEMG, cometa S.r.l., Italy), a motion capture system (OptiTrack, NaturalPoint, Inc., USA), and the fitness equipment listed above for outdoor experiments.

In all experiments, a natural latex rubber resistance band (Band, TheraBand, USA) attached to carabiners, which are secured to straps fastened around the ankle was used as the exotendon. The length of the exotendon is 25% of the subject's leg length measured from the anterior superior iliac spine to the medial malleolus. This can be seen in figure 1.

2.3 Experiments

2.3.1 Outdoor Experiments

To analyze the effect of an exotendon on various steepness grades, we conducted outdoor experiments consisting of 2 subjects, with one using a 60 N m^{-1} resistance band and the other using a 120 N m^{-1} band. Both subjects went through 2 trials on consecutive days, 1 trial consisting of a 5-minute warm up, 1 natural run, and 1 exotendon run. Both runs had a prescribed speed of 2.67 m s^{-1} and a 5-minute resting period both before the natural run and exotendon run.

The course chosen consisted of a flat section with +0.6% grade incline followed by a decline of -4.6%. The roundtrip then consisted of a +4.6% grade incline followed by a -0.6% decline. Flat sections for the 2-kilometer run comprised 58% of the route, while both declines and inclines comprised 42% of the route. Both subjects were instructed to remain at the prescribed speed the entire run.

2.3.2 Indoor Experiments

Indoor experiments were conducted to validate findings from outdoor results. These experiments contained 5 subjects, with 4 using a 60 N m^{-1} resistance band and 1 using a 120 N m^{-1} band. Once again, each subject completed 2 trials, with 1 trial occurring on 2 consecutive days. 1 trial consisted of a light 5-minute warm up followed by 5 minutes of rest. Natural and exotendon runs were then alternated between 4 times with 5-minutes rests in between each iteration. Each run for both natural and exotendon iterations was 10 minutes long with a constant prescribed speed of 2.67 m s^{-1}.

To investigate change in major leg-muscle activity, non-invasive EMG electrodes were placed on 8 major leg muscles throughout each experiment. Muscles analyzed consisted of the gluteus maximus, iliopsoas, semitendinosus, rectus femoris, vastus lateralis, biceps femoris, soleus, and tibialis anterior on both legs. Before each trials' warm-up, maximum voluntary contractions (MVCs) were measured from each participant for later normalization of EMG data in analysis.

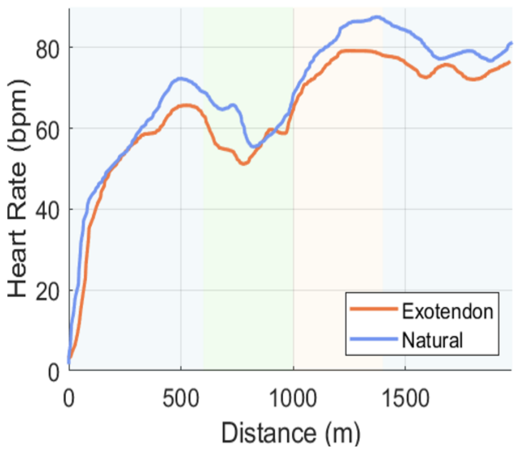

Figure 2: Net Heart Rate Comparison

To investigate overall force in the direction of work, ground reaction forces were recorded throughout each iteration.

3. Data Analysis

3.1 Outdoor Analysis

Energy Expenditure Analysis

Due to outdoor constraints, respiratory gas analysis for collecting energy expenditure data was not possible. An accurate alternative however [4] makes use of net heart rate (NHR) as well as subject body weight for an accurate replacement measurement. Net heart rate is calculated by subtracting a subject's active heart rate during iterations by their resting heart rate measured beforehand. This resting heart rate is calculated by taking the average of the last 2-minutes of a resting period directly before the natural or exotendon iteration begins. This removes variability of heart rate due to both exhaustion as well as external factors such as varying weather and pedestrian obstacles. Once collected, this net heart rate data was bandpass filtered (4^{th} order, zero-phase shift Butterworth).

With net heart rate found, calculating net energy expenditure (NEE) (in kcal min^{-1}) only requires a subject's body weight and the following equation [4]:

$$NEE = 1.012 - 0.0154 \times NHR + 0.01140 \times weight + 0.00192 \times NHR \times weight$$

With this equation, net energy expenditure was averaged over flat, inclined, and declined intervals for both natural and exotendon runs. For both 60 N m^{-1} and 120 N m^{-1} experiments, averages of exotendon runs were compared against natural runs to reveal improvements or detriments in net energy expenditure based on steepness grade. Each run was separated based on steepness grade before averages were taken. Step cadence averages of both natural and exotendon runs were compared as well.

3.2 Indoor Analysis

Electromyography

Analysis of 8 major leg muscles were recorded. These muscles include the gluteus maximus, iliopsoas, semitendinosus, rectus femoris, vastus lateralis, biceps femoris, soleus, and tibialis anterior on both legs. Electromyograms for each muscle were bandpass filtered at 20-400 Hz (4th order, zero-phase shift Butterworth). Measured muscle activity was then normalized against collected MVC values and averaged over a full gait cycle for both dominant and non-dominant legs. Minutes 2 through 5 were considered for this averaged gait cycle to remove major outliers at the beginning and end of data sets as well as remove variability from some EMG electrodes falling off or loosening over time. Any gait cycle averages not within 3 standard deviations of the mean were removed to maintain accuracy of averages.

These averages for the 2 sets of alternating natural and exotendon runs of each trial were then compared against one another for analysis. For each trial, runs 1 and 2 were compared while separately, runs 3 and 4 were compared. This method of analysis eliminates the affect fatigue from overall results. Percent differences between overall means of gait cycles were recorded for each set (2 vs. 1 and 4 vs. 3). Two-tailed paired t-tests were employed for comparison between exotendon and natural averages.

Once accurate averages were established for each muscle, muscles were grouped into four areas (hip, quadricep, hamstring, lower leg) for further analysis. It isn't sufficient to simply see lower muscle activity and state it as an improvement or detriment since step cadence increases when the exotendon is applied thus requiring more steps to complete the same amount of work. Due to this fact, the following equation is employed to factor in more frequent steps along with changes in averaged muscle activity. Net change (NC) equals the percent difference of cadence (C) and muscle activity (MA) after both average cadence difference (1.02) and muscle activity percent difference (PD) is applied.

$$NC = \left(\frac{C \times MA \times (1.02 \times PD) - (C \times MA)}{(C \times MA)}\right) \times 100$$

To simplify calculations, cadence change between exotendon, and natural running was averaged over all outdoor experiments resulting in a 2% increase due to exotendon intervention. This equation was employed for both 60 N m^{-1} and 120 N m^{-1} iterations in all four muscle groups. NC values were compared between exotendon and natural runs instead of simply muscle activity means.

Ground Reaction Forces

Although reaction forces in three different planes were recorded, only reaction forces in the direction of work were analyzed. This is due to the hypothesis that the required total force to produce the same amount of work will be less when an exotendon is intervening, due to running economy becoming more efficient. Ground reaction forces, similarly to electromyograms were bandpass filtered at 20-400 Hz (4th order, zero-phase shift Butterworth). Reaction forces were then averaged over a full gait cycle for both dominant and non-dominant legs. Minutes 2 through 8 were used for analysis to remove outliers found in the beginning and end of data sets. Any averaged cycle above a standard deviation of 3 from the mean was removed from analysis to maintain accuracy.

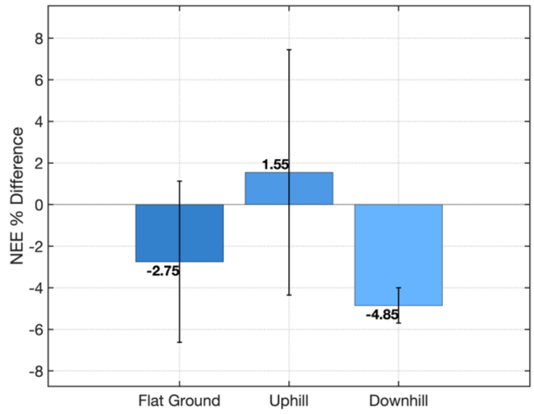

Figure 3: Net Energy Expenditure Percent Differences (60 N m^{-1})

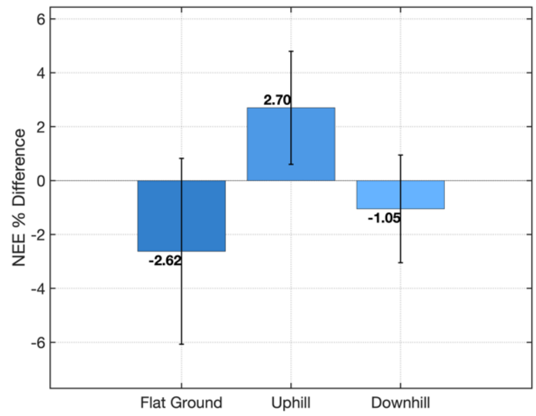

Figure 4: Net Energy Expenditure Percent Differences (120 N m^{-1})

Once again, for each trial, runs 1 and 2 were compared while separately runs 3 and 4 were compared. This method of analysis eliminates the affect fatigue from overall results. Percent differences between overall means of gait cycles and overall maximum amplitude were recorded for each set (2 vs. 1 and 4 vs. 3). Two-tailed paired t-tests were employed for comparison of gait cycle averages for natural and exotendon running.

4. Results

4.1 Outdoor Results

We found that net energy expenditure (NEE) (in kcal m^{-1}) for both 60 N m^{-1} and 120 N m^{-1} trials became more efficient in flat and declined steepness grades, while inclined grades saw negative impact. Running on relatively flat ground (±0.6% grade) saw a -2.75% decrease in average NEE when a 60 N m^{-1} resistance band was employed (Fig.3). This is consistent with the impact of the 120 N m^{-1} band which saw -2.62% change in NEE with exotendon intervention (Fig.4). When running on a steepness grade of 4.6%, intervention with both resistance band strengths saw a detrimental impact ranging from a 1.55% to 2.70% increase in NEE (Fig. 3, Fig. 4). Finally,

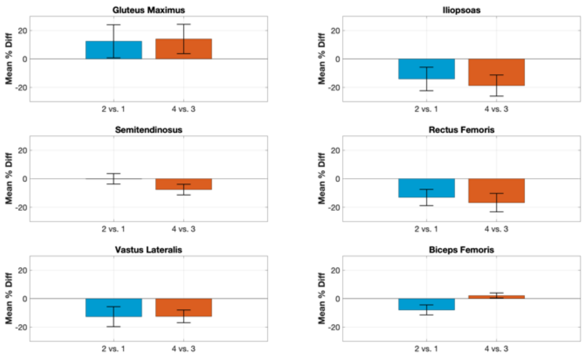

Figure 5: Percent Change in Muscle Activity (60 N m⁻¹)

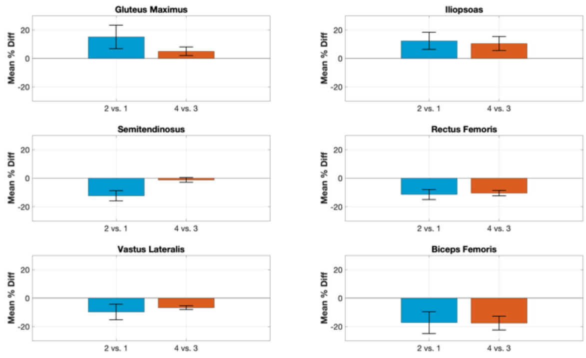

Figure 6: Percent Change in Muscle Activity (120 N m⁻¹)

when applied in a downhill grade of -4.6%, high variability was found between exotendon strength while both proved beneficial. With the stronger exotendon, a -1.05% decrease in average NEE with intervention was seen (Fig.4). With the moderate exotendon, a -4.85% difference occurred (Fig. 3).

4.2 Indoor Results

Indoor experiments found that in both 60 N m^{-1} and 120 N m^{-1} iterations, major hip muscles saw increased muscle activity while quadricep and hamstring muscles saw decreased muscle activity over each gait cycle (Fig. 7). Lower leg muscle (tibialis anterior, soleus) reduction or growth was found to be statistically insignificant. All reduction or growth in muscle activity factored in an averaged 2% increase in step cadence as explained previously (Fig.7). For 60 N m^{-1} iterations, the gluteus maximus and iliopsoas saw an overall 0.37% increase in muscle activity. This however only differs from the stronger exotendon strength in that the iliopsoas saw improvement. The quadriceps group of the rectus femoris and vastus lateralis saw a -12.06% decrease in muscle activity. The hamstring group saw a -1.48% decrease in muscle activity. In 120 N m^{-1} iterations, the gluteus maximus and iliopsoas saw an increase of 12.30% in muscle activity during exotendon intervention. The rectus femoris and vastus lateralis experienced a -7.80% decrease in muscle activity while the semitendinosus and biceps femoris saw a -10.30% decrease in activity. Lower leg increases or decreases in muscle activity was once again statistically insignificant, possibly due to higher presence of noise and smaller signal amplitudes created by smaller muscle groups.

Ground reaction force analysis in the direction of work was also inconclusive. All reduction or growth in max amplitude or average mean of newtons in the direction of work was insignificant.

5. Discussion

This specific study sheds light on the applicability of an "exotendon" in various steepness grades outdoors. It additionally analyzes the different impacts of varying resistant strengths. The results from this study support previous findings [1] that overall running economy improves on flat ground. Seen in net energy expenditure impact due to exotendon intervention (Fig. 3, Fig. 4),

	60 N/m	120 N/m
Hip	0.37%	12.30%
Quadriceps	-12.06%	-7.80%
Hamstrings	-1.48%	-10.30%

Figure 7: Percent Change in Major Muscle Groups

these benefits do also apply to declined slopes while inclined benefits remain limited. The indoor portion of experiments, serving as validation for outdoor experiments, revealed varying muscle activity due to exotendon intervention. For both 60 N m^{-1} and 120 N m^{-1} resistance strengths, major hip muscles saw increases in activity while major quadricep and hamstring muscles saw continuous decreases. While 120 N m^{-1} iterations caused a greater activation in hip muscles (both the gluteus maximus and iliopsoas), there was greater reduction in hamstring muscle activity. The inverse can be seen in 60 N m^{-1} iterations (Fig. 7) while both exotendon strengths consistently improved upon quadricep muscle activation. It is worth noting that downhill improvement in running economy for 60 N m^{-1} iterations was greater than the stronger exotendon with nearly a 5% larger decrease. Flat portions also saw greater improvement, but only slightly with a .13% difference. This along with the improvement seen in the iliopsoas muscle indicates that moderate-strength resistant bands may be more effective in improving running economy.

The intervention of an exotendon in basic running cycles introduces many changes. In both stance and swing phase, it produces moments at each ankle drawing the legs together. This results in the step cadence increase consistently seen in previous studies. As far as major muscle activity output is impacted, there is not a direct correlation found in the results of this study for explanation. Simpson et al. [1] reveals a reduction in both required joint moments and power to achieve the same work after exotendon intervention. Improvements seen in mean muscle activity for both the quadriceps and hamstrings from this study could be a result of these kinematic improvements.

Although it has proven an accurate alternative for respiratory gas analysis [4], the use of net heart rate in evaluating net energy expenditure relies entirely on the resting heart rate average taken before any given run, whether that be exotendon or natural. Although averages are taken of the resting heart rate for 2 minutes before each run to remove some variability, this value can vary heavily from subject to subject. If future studies rely on this method of analysis completely, greater sample sizes should be employed to combat the variable nature of net heart rate analysis. This experimental issue could also be why energy expenditure improvement is around 4% less when compared to previous studies [1].

A question remains as to why ground reaction force analysis in the direction of work didn't result in any significant difference after exotendon intervention. Exotendon intervention theoretically funnels more energy expended during running towards leg swing instead of stabilizing the center of mass, which wouldn't necessarily affect the overall generation of force in the direction of work. Exotendon effects could simply find more efficient ways of generating this necessary amount of force which could result in the insignificant change seen. While the average force stays relatively the same, the energy used to generate such a force becomes more efficient.

This study adds onto previous investigation of an exotendon's benefits in augmenting human running. Results indicate beneficial effects for varying resistant strengths in both flat and declined steepness grades while inclined application is detrimental. While major muscles in both the quadricep and hamstring group see lower muscle activity, hip muscles see higher activity. Hip muscle activity effects are less impactful, however, specifically with 60 N m^{-1} results. To improve on this study, larger sample sizes are required. The use of net heart rate as a method of analysis raises possible concerns to the validity of net energy expenditure results from the outdoor trials. Additionally, testing outdoors allows variable weather patterns to affect results which gives even more reason for an increase in sample size. Indoor findings suggest that depending on the strength of exotendon used, different muscle groups benefit. Further investigation could reveal more effective results from strengths not yet tested. From exotendon strengths used in these experiments, evidence consistently indicates that an exotendon when applied outdoors aids overall running economy on flat and declined grounds while harming running economy on inclined paths.

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