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Fatigue induced changes in eggbeater kick kinematics affect performance and risk of injury

Original Investigation

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Abstract

Purpose: To investigate the effects of fatigue on the vertical force and kinematics of the lower limbs during maximal water polo eggbeater kicking. **Methods:** Twelve male water polo players maintained as high a position as possible while performing the eggbeater kick with the upper limbs raised out of the water, until they were unable to keep the top of the sternum (manubrium) above water. Data comprising twenty-seven complete eggbeater kick cycles were extracted corresponding to nine cycles of the initial non-fatigued (0%), 50% time point (50%) and final fatigued (100%) periods of the trial. Vertical force, foot speed, and hip, knee and ankle joint angles were calculated. **Results:** Mean vertical force (0%: 212.2N, 50%: 184.5N, 100%: 164.3N) progressively decreased with time. Speed of the feet (0.4m/s), hip abduction (2.9°) and flexion (3.6°) decreased with fatigue while hip internal rotation (3.6°) and ankle inversion (4°) increased with fatigue. Average angular velocity decreased for all joint motions. **Conclusions:** Eggbeater kick performance decreases with fatigue. Inability to maintain foot speeds, and hip and ankle actions with progressing fatigue diminishes the ability of the player to produce vertical force during the cycle. Increased internal rotation of the hip when fatigued, and the large eversion/abduction of the ankle during the cycle may be a predisposing factor for the prevalence of patellofemoral pain syndrome observed among eggbeater kick performers. Appropriate training interventions that can limit the effects of fatigue on performance and injury risk should be considered.

Keywords: Athletic Performance; Maximal Effort; Lower Extremity; Water Polo; Synchronized Swimming;

Introduction

The eggbeater kick is a fundamental technique used in water polo and synchronized swimming. In water polo it can be used up to 45 to 55% of the game[1]. It is particularly important to keep the upper body elevated above water to execute passing, shooting and blocking actions or to push an opponent[1]. Moreover, the performance of these skills has been shown to be positively affected by the height attained out of the water[2] and is therefore dependent on the vertical force players are able to produce from the eggbeater kick.

Fatigue has been defined as a decrease in the force and power-generating ability of the neuromuscular system[3]. Thus, the vertical force produced during the eggbeater kick can decline with fatigue and match performance be affected. Information on the vertical force produced can be obtained during the execution of the eggbeater kick[4,5] and its decrease reflects the progression of fatigue during the movement.

Some studies have focused on the movement of the lower limbs during the eggbeater kick and the technique associated with better performance[5,6,7]. Sanders[7] reported the orientation of the lower limbs and speed of the feet as factors influencing the height attained during the eggbeater kick. The sculling motion of the feet should keep high speeds throughout the whole cycle and emphasize horizontal motions favorable to create lift forces. Other studies[5,6] observed that better eggbeater kick performers kept the knees wide and close to the water surface through hip abduction and flexion. Additionally, it is suggested the heels should be brought high for the outkick enabling subsequent strong internal rotation of the hips that contributes to foot speed. However, further information about the individual joint motions involved in the eggbeater kick and how they change with fatigue is needed to identify possible limitations to performance, and risks of overuse injury.

First, it is important to understand the consequences of fatigue on the eggbeater kick technique to develop appropriate training interventions that can address the limitations from fatigue in performance. The decrease in eggbeater kick performance during fatigue could be attributed to the water polo player being unable to maintain the speed of the feet and/or maintain an optimal movement pattern and orientation of the feet. Second, the excessive repetitive use of the eggbeater kick motion has been referenced as the cause for lower limb injuries such as patellofemoral syndrome[8,9,10], chronic overuse injury in the knee[11], adductor muscle strains or tenosynovitis of the extensor longus tendon[12]. Understanding the amplitude and range of motion of independent joint motions and how it changes with fatigue is critical to developing therapies[13] and interventions that may minimize adverse fatigue effects and target fatigue responses.

With this in mind, the purpose of this study was to evaluate the changes associated with fatigue in lower limb kinematics and kinetics while attempting to maintain maximal above-water height of the upper body during the eggbeater kick.

Methods

Twelve national division one level male water polo players (aged: 22.41 ± 1.50 years; body mass: 81.25 ± 6.08 kg; height: 184.75 ± 5.11 cm) were tested. At the time of this study, the participants had 4–5 sessions of water polo training per week. Written informed consent was obtained from the participants for all the procedures. This investigation conformed to the *Code of Ethics of the World Medical Association* and the study was granted ethical approval by the University of Edinburgh Ethics Committee.

For the test, each player was asked to execute the eggbeater kick in a swimming pool with the trunk aligned vertically and with the arms elevated above the water while trying to maintain as high a position as possible for its duration. The test finished when the black tape placed on the superior part of the sternum (manubrium) was not visible. This moment was considered to be the time that the level of fatigue was sufficient to prevent the player from continuing to sustain that criterion height (100% of time to fatigue).

This study followed a one group repeated measures design. Nine eggbeater kick cycles were sampled at three different times in the test (0%, 50%, 100% of the time to fatigue). The cycle was defined as the period between two consecutive maximum knee extensions of the dominant leg.

Before the test each participant's lower limb (pelvis, thigh, shank and foot) was marked with red and black spherical markers positioned in specific anatomical landmarks. With these markers four coordinate frames identifying each lower limb segment were created[4,5]. Subsequently, orientations of the anatomical axis systems for pelvis, thigh, shank and foot were determined and orientation of distal segments were expressed relative to proximal segments. The sequence of rotation for the hip was flexion/extension, abduction/adduction and internal/external rotation. The ankle followed the same sequence but different terminology was adopted: plantarflexion/dorsiflexion, inversion/eversion and adduction/abduction. Given the small amplitude of knee valgus and rotation motions and the inherent measurement error associated with it, only flexion/extension was considered for the knee joint[4,5]. Speed of the feet was calculated following the methods outlined by Sanders[14]. To calculate the vertical force produced during the eggbeater kick cycle an additional marker was used. A black tape (5cm x 1.9cm) on a white tape background was placed in the superior part of the sternum (manubrium) to enable the calculation of a regression curve for height/weight-plus-buoyancy for each participant[4,5], and the subject's height above the water during the test. Vertical force was calculated by adding derived kinetics data from participant specific body segment parameter data[15], and the weight-plus-buoyancy from the regression curve[4,5].

Five portable ELMO PTC-450C cameras (4 cameras below and 1 above the water surface) recorded the movement at 25 frames per second. Underwater cameras were placed 5m away from the subject and were inside a waterproof box that could be attached in any place on the swimming pool wall thereby enabling optimal positioning to capture all markers by at least two cameras throughout the kick cycle. The above water camera was placed 7m away from the subject horizontally aligned with the subject. The camera and calibration procedure for the three dimensional analysis of the lower limb motion was adapted from Psycharakis & Sanders[16].

All variables were calculated using a custom made MATLAB software (version R2012a). Prior to calculating variables data were filtered with a 2nd order Butterworth filter with a 6Hz cut-off frequency and interpolated to a 1600Hz frequency signal using a cubic spline function. All joint angles were referenced from anatomical posture. Hip, knee, and ankle angles for both dominant and non-dominant sides were analyzed to ensure no major discrepancies were evident.

Descriptive statistics are presented as mean ± SD. Normality of the distribution of the data was checked by the Shapiro–Wilk normality test, and the kinematic and kinetic variables were compared at 0, 50 and 100% of time to fatigue using a one-way repeated-measures ANOVA with an alpha level of 0.05. Post hoc pair-wise analysis was also performed and a Bonferroni adjustment made for multiple comparisons. Differences between fatigue levels at equivalent percentiles of the kick cycle were manifest as disjoint envelopes of 95% confidence intervals of the true mean of the nine cycles of each fatigue level on an individual participant basis.

Results

The average total time until fatigue was 30.6 ± 4.0s. There was a significant ($P<.001$ for all levels) reduction in the mean vertical force produced during the cycle (0%, 212.2 ± 27.6N; 50%, 184.5 ± 21.6N; 100%, 164.3 ± 22.2N). Average speed of the feet decreased significantly ($P<.001$ for all levels) with fatigue (0%, 2.7 ± 0.1m/s; 50%, 2.5 ± 0.1m/s; 100%, 2.3 ± 0.1m/s) which resulted in increased duration of the cycles (0%, 0.51 ± 0.03s; 50%, 0.56 ± 0.03s; 100%, 0.59 ± 0.03s). Figure 1 shows vertical force reduced with fatigue throughout the whole cycle, and particularly during the time near the positive force peaks for which the difference between fatigue conditions was consistently significant statistically. This corresponded to the part in the cycle during which the knee was being extended.

******Figure 1******

Table 1 shows the scores across all subjects for the joint angles calculated for the three fatigue levels. Average hip abduction (0/100%, $P=.012$; 50/100%, $P=.037$) and flexion (0/100%, $P=.027$) angles decreased, and hip internal rotation (0/100%, $P=.009$) increased when fatigued. The hip maintained range of motion for all motions across fatigue levels. The knee reduced its range of motion (50/100%, $P=.045$) with fatigue by decreasing its maximum flexion (0/100%, $P=.011$) while maintaining its maximum extension. The ankle increased inversion ($P<.001$) and decreased maximum dorsiflexion (0/100%, $P<.001$; 50/100%, $P=.048$; 0/50%, $P<.001$) and flexion range of motion (0/100%, $P<.001$; 0/50%, $P=.001$) with fatigue. Angular velocity decreased at all joints.

Figure 2 show typical patterns of hip, knee and ankle joint motions at 0 and 100% time to fatigue throughout an eggbeater kick cycle.

*******Table 1*********

*******Figure 2********

Discussion

This study investigated fatigue-related changes in the kinematics and kinetics of the water polo eggbeater kick to provide foundational knowledge to underpin training programs related to optimizing performance and minimizing injuries.

The reduction in the vertical force produced by the eggbeater kick action in time demonstrates the inability of the players to maintain eggbeater kick performance with the progress of fatigue. This can be explained as the result of some changes that occur in the movement.

One of the main indicators of fatigue was the decrease of cycle rate. With fatigue, players tended to increase the duration of the cycle while maintaining the range of motion for most motions with the exception of knee flexion-extension and ankle plantarflexion-dorsiflexion. Increasing the cycle time with fatigue differs from other cyclical aquatic sports such as swimming[17] where cycle time decreases in an attempt to maintain swimming speed despite reduction in the forces applied. This difference in fatigue adaptations of the movement between swimming strokes and the water polo eggbeater kick might be explained by the fact that the above water recovery in swimming strokes affords the opportunity to increase stroke rate with only small increases in resistance to the motion. This means that reducing recovery time is an efficient way to increase stroke frequency. Additionally, the pull phase of the swimming stroke can be shortened by decreasing the range of motion or by changing the orientation of the hand to reduce the resistive force so that stroke rate can be maintained despite fatigue. In contrast, the range of joint motion and resistance to motion cannot be changed readily in the eggbeater kick without further adverse effects on performance. The hip needs to rotate internally and the ankle needs to evert and abduct to create favorable pitch angles during knee extension. At the same time, the knee needs a large range of motion to create high foot speed and take advantage of the favorable pitch angles[4,7]. Although fatigue has been related to declines in range of motion of the lower limbs for activities such as squats[18], jumps and side-step skills[19], range of motion during the eggbeater kick was maintained for most joint motions. However maintaining range of motion usually meant reducing amplitude of anatomical angles.

Players conserved hip abduction and flexion range of motion by moving maximum and minimum angles towards the neutral anatomic position (0°). It would appear that the neutral position minimizes the demand on the muscles. By contrast increasing internal rotation might be an adaptation of the hip joint to compensate for the inability to abduct and flex with fatigue, meaning that internally rotating the hip, while not as effective in the technique, might be less demanding in terms of muscle activity than abducting and flexing the hips. The knee maintained its maximum extension but reduced its maximum flexion, suggesting that the phase of the cycle where the knee was flexed might have been more demanding than the phase when the knee was extended.

The joint angles during the eggbeater kick cycle reveal greater demand for specific joint motions during this technique compared with other activities. While hip flexion and abduction angles and range of motion seem to be within the values reported for many activities[20,21,22], hip internal rotation seems to be considerably greater in the eggbeater kick compared with running[20] or cycling[22]. Similarly, knee flexion/extension range of motion in the eggbeater kick is greater than reported for cycling[22], and running at slower speeds[20] but identical to running at higher speeds[21]. Because the eggbeater kick does not have a support phase during its cycle, and it relies strongly on the orientation of the feet to create propulsive forces, one might expect large amplitude and ranges of motions for the ankle joint. Ankle maximum plantarflexion, inversion and adduction during the eggbeater kick were greater than the values reported for daily activities, such as walking[23], or sports movements such as running[24,21] or cycling[22].

As a cyclical movement, the repetition of the previously mentioned joint motions can be interpreted as a risk factor for potential overuse injuries. Abnormal eversion of the ankle (i.e. amount of motion is excessive or occurs at the wrong time)[25,26] and excessive internal rotation of the hip have been suggested to be associated with patellofemoral pain[27,28]. Moreover, large internal rotation of the hip with large eversion/abduction of the ankle, a typical position during the eggbeater kick cycle, has been suggested to contribute to abnormal alignment of the patellofemoral joint and increase the risk of patellofemoral dysfunction[29,30]. Additionally, it has been demonstrated that the influence of hip internal rotation in the malalignment of the patella was more noticeable when the knee was closer to terminal knee extension (approx. 30°) as opposed to greater flexion angles[27,28]. In this study, internal rotation of the hip has been shown to increase with fatigue while maximum knee flexion has been shown to decrease, meaning that fatigued motion will tend to have the hip more internally rotated and the knee less flexed thereby encouraging misalignment of the patella and predisposing risk of injury. Moreover, the phase of the cycle when the hip is internally rotated occurs at the same time the ankle is everted and abducted, and close to maximum extension of the knee. Therefore, the fatigue process in the eggbeater kick is likely to expose performers to greater risk of patellofemoral injury.

Practical Implications

Eggbeater kick performers cannot maintain the production of vertical force during 30s of maximal eggbeater kick. Fatigue during sustained maximal eggbeater kick tends to reduce hip abduction and hip flexion, and increase hip internal rotation. This can present increased risk of patellofemoral pain syndrome in the eggbeater kick. Specific training concentrated on the hip abductors and flexors is recommended to delay the onset of fatigue in these muscle groups and the respective compensatory motion of increasing hip internal rotation. This can be achieved through land-based fatigue resistant training programs or therapies that facilitate hip abduction and flexion. Moreover, periodization of training is important to avoid long periods of maximal eggbeater kick execution. Future training and injury prevention strategies may need to consider reducing negative effects of fatigue.

Conclusion

This study addressed the decline in performance associated with fatigue during the eggbeater kick, and the overuse injury risk associated with repetition of excessive joint motions. First, the decline in the vertical force created during the eggbeater kick due to fatigue was associated with decreased speed of the feet which reduced cycle frequency. Additionally, average, maximum and minimum hip abduction and flexion decreased while hip internal rotation increased with fatigue. Second, the increased internal rotation of the hip with fatigue, combined with eversion/abduction of the ankle when the knee is extending might be associated with the prevalence of patellofemoral pain syndrome observed among eggbeater kick performers. These findings can help coaches designing training interventions that could delay the onset of fatigued movement patterns in the eggbeater kick, as well as allow clinicians and athletic trainers to develop successful therapies to reduce injury risk in the eggbeater kick.

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Table 1. Mean (SD) of joint variables calculated at non-fatigued (0%), 50% time point (50%) and fatigued (100%) levels across all subjects.

	Time to Fatigue	Hip Abduction	Hip Flexion	Hip Internal Rotation	Knee Flexion	Ankle Inversion	Ankle Plantarflexion	Ankle Adduction
Average (°)	0%	34.0* (7.2)	45.5* (10.3)	20.3* (8.0)	91.0 (4.9)	2.2** (3.1)	20.7 (4.5)	20.7 (8.5)
	50%	32.5* (6.0)	42.9 (8.8)	22.9 (7.6)	89.6 (5.0)	5.3* (3.3)	20.7 (4.6)	20.9 (8.6)
	100%	31.1** (5.1)	41.9* (7.9)	23.9* (7.7)	89.0 (3.8)	6.2* (3.1)	20.8 (4.7)	21.1 (8.2)
Maximum (°)	0%	40.8* (8.0)	64.1* (14.1)	46.8* (8.8)	142.3* (5.6)	25.3 (5.8)	44.5 (3.9)	43.7 (10.3)
	50%	39.3 (7.5)	60.5 (11.6)	50.4 (7.7)	140.7 (5.6)	27.0 (5.5)	43.9 (4.4)	43.7 (10.5)
	100%	37.9* (6.5)	59.0* (10.6)	51.0* (8.0)	138.6* (5.1)	26.1 (5.4)	43.0 (3.9)	43.3 (8.9)
Minimum (°)	0%	7.3* (7.3)	31.2** (7.6)	-12.1 (11.6)	37.9 (8.8)	-9.1 (6.7)	-18.2** (4.7)	-4.0 (10.8)
	50%	5.8 (5.8)	28.6* (6.1)	-11.1* (11.5)	35.7 (8.4)	-8.9 (6.1)	-14.5** (5.4)	-4.5 (10.3)
	100%	4.3* (4.9)	27.7* (5.5)	-8.2* (11.0)	36.7 (7.4)	-8.9 (5.8)	-12.8** (3.2)	-4.0 (8.7)
Range of Motion (°)	0%	33.4 (3.3)	32.8 (9.1)	59.0 (10.6)	104.4 (11.2)	34.4 (4.1)	62.8** (7.6)	48.2 (12.1)
	50%	33.5 (3.9)	31.9 (7.2)	61.6 (11.2)	105.0* (10.6)	35.9 (4.6)	58.4* (8.1)	48.1 (13.4)
	100%	33.5 (3.5)	31.2 (7.4)	59.3 (11.5)	101.9* (10.6)	35.1 (4.7)	56.0* (6.1)	47.4 (11.2)
Average Angular Vel. (°/s)	0%	245.5** (46.3)	208.9* (31.2)	229.8** (47.6)	316.6** (35.1)	225.8** (23.7)	263.8** (42.5)	303.0** (53.5)
	50%	147.7* (25.1)	199.0* (21.3)	208.7** (35.1)	283.9** (33.5)	203.8** (20.4)	236.6** (39.7)	283.4** (43.7)
	100%	137.7* (19.3)	182.3** (17.4)	186.9** (30.2)	259.4** (24.9)	180.5** (22.3)	215.6** (29.3)	265.8** (36.6)

[*] indicate statistical significant differences ($p<0.05$) between fatigue levels.

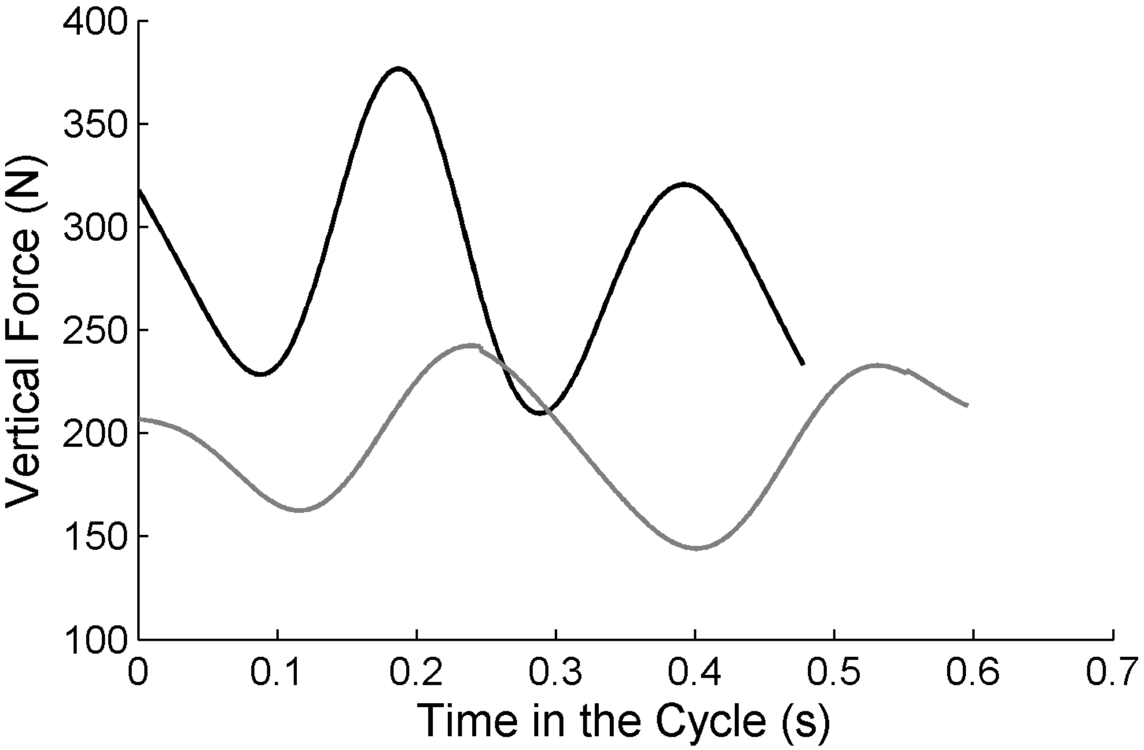

Figure 1. Vertical force during one eggbeater kick cycle at 0 (black line) and 100% (gray line) of time to fatigue.

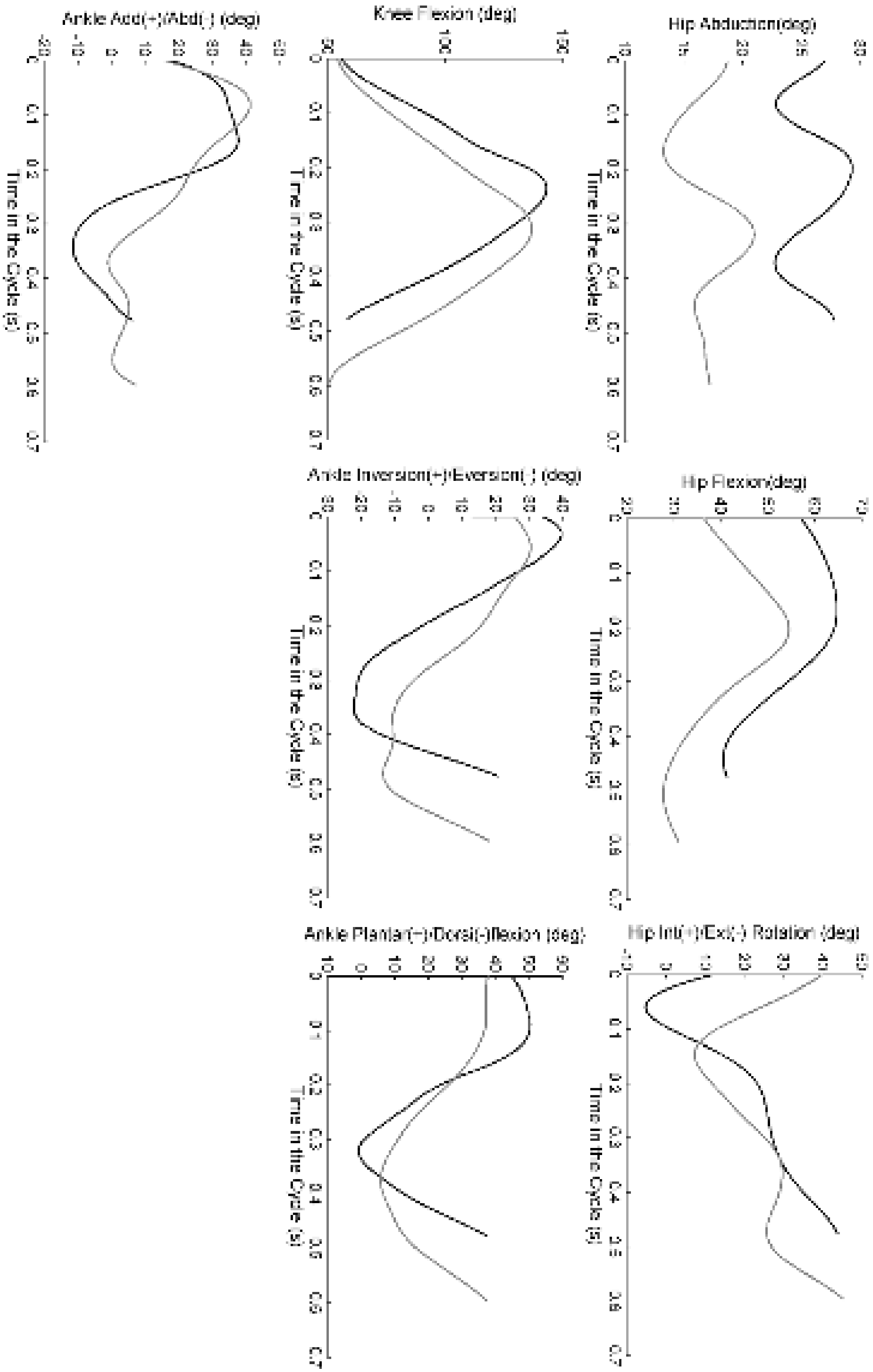
Hip Abduction(deg)
10
15
20
25
30
Hip Flexion(deg)
20
30
40
50
60
70
Hip Int(+)/Ext(-) Rotation (deg)
-10
0
10
20
30
40
50
Knee Flexion (deg)
0
100
150
Ankle Inversion(+)/Eversion(-) (deg)
-30
-20
-10
0
10
20
30
40
Ankle Plantar(+)/Dorsi(-)flexion (deg)
-10
0
10
20
30
40
50
60
Ankle Add(+)/Abd(-) (deg)
-20
-10
0
10
20
30
40
50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time in the Cycle (s)

Figure 2. Right hip, knee and ankle joint angles during one eggbeater kick cycle at 0 (black line) and 100% (gray line) of time to fatigue.