# INVESTIGATION OF ATM PROPULSION FORCE-TIME PROFILES USING FUNCTIONAL DATA ANALYSIS ON FRONT CRAWL SPRINT SWIMMERS

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The purpose of this investigation was to assess whether characteristics of the Assisted Towing Method (ATM) propulsive force-time profiles can discriminate between elite and sub-elite male sprint swimmers. Eleven elite and seven sub-elite sprint front crawl swimmers completed the ATM protocol to capture propulsion force-time profiles. The second full stroke cycle taken from the median propulsion trial on both the right and left arms were selected and functional data analysis was used to process the trials. Functional principal components analysis (*f*PCA) results revealed a statistical difference between the elite and sub-elite groups ($p$ > 0.000). Further, within the elite group profiles, a distinctive double peak was found. The double peak profile could suggest a more efficient and effective stroking ratio of active drag and propulsion within the elite group.

**KEY WORDS:** Swimming, functional principal component analysis.

**INTRODUCTION:** Free swim analysis has been assessed using the assisted towing method (ATM) for almost a decade. This protocol captures active drag and propulsion in free swimming by comparing the velocity differences between free swim maximal effort and an assisted (towed) maximal swim with regard to the added assistance used to tow the swimmer. Early work using the ATM only presented mean active drag values, however more recently, studies have presented both active drag and propulsion force-time profiles to further analyse free swimming (Mason, Sacilotto, Hazrati, & Franco, 2014; Sacilotto, Franco, Mason & Ball, 2013). Using the current fluctuating tow protocol, Mason, Sacilotto and Menzies (2011) reported that a more realistic curve was produced than from the original constant tow investigations (Formosa, Mason, & Burkett 2010). Further work has since utilised the fluctuating tow protocol and has started to define the characteristics of these force-time profiles in an attempt to determine if they are an accurate representation of free swimming and whether there are common characteristics between swimmers. Sacilotto et al (2013) identified a common biphasic pattern within an elite male sample (Figure 1a). Moreover, the previous work also found an inconsistent multiphasic pattern within the sub-elite male sample (Figure 1b). These findings led Sacilotto et al (2013) to hypothesise that there is an optimal ratio of active drag and propulsion which produces a consistent biphasic pattern within elite sprint front crawl swimmers.

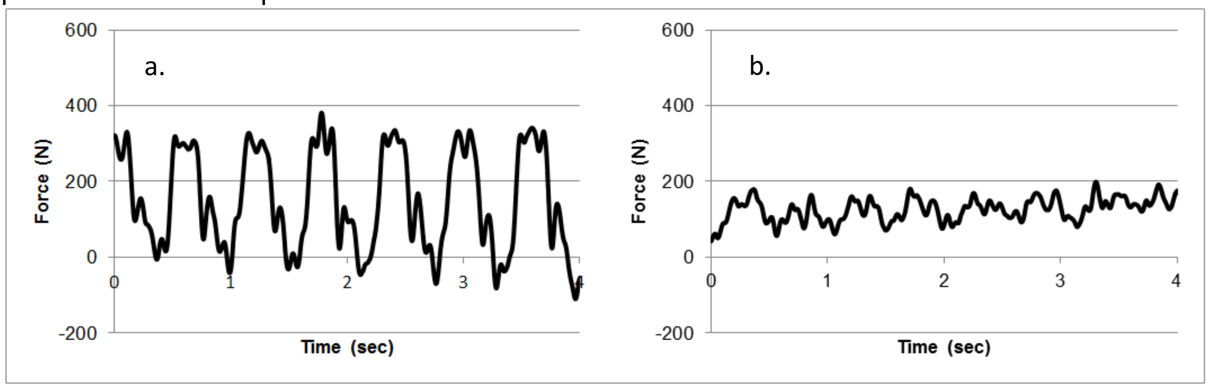


**Figure 1: Example of individual swimmer ATM propulsion force-time profiles. a. Elite at 1.95 m/s swim velocity and 2.07 m/s tow velocity; b. Sub-elite at 1.81 m/s and 1.96 m/s tow velocity. Adapted from Sacilotto et al (2013).**

As noted, the next phase of investigating the ATM force-time profiles is to identify the characteristics of the curves and whether an optimal profile exists. Qualitative analysis of the propulsive male force-time profiles in Sacilotto et al (2013) concluded that the elite sample had a consistent stroking pattern. Whilst quantitative results revealed no statistical difference between the time spent in each stroke phase between the elite and sub-elite groups, the reasoning for the difference in curve characteristics was suggested to be due to elite swimmers producing a more efficient underwater (i.e. propulsive) phase. Without the availability of inertial sensor technology, the application of functional data analysis (FDA) was explored to further investigate propulsive force-time profiles.
One FDA strategy with potential applicability for investigating differences in the shape of force-time profiles is 'Functional Principal Components Analysis' (*f*PCA) (Ramsay, 2006). The benefits of *f*PCA for assessing trends in biomechanical variables have already been highlighted in research assessing vertical jump performance (Ryan, Harrison & Hayes, 2006). In swimming the propulsive force-time profiles could be analysed using *f*PCA and the results of this analysis could be used to discriminate between swimmers of differing performance levels. Therefore, the purpose of this investigation was to identify whether the consistencies found in force-time profiles from qualitative analysis could be confirmed via the use of FDA. It was hypothesised that *f*PCA will be able to discriminate elite and sub-elite force-time profiles.

**METHODS:** Eleven elite and seven sub-elite male front crawl sprint swimmers (Elite: 1.90 ± 0.05 m/s swim velocity; 789 ± 76 FINA points; and 50.85 ± 1.56 s 100 m performance best time. Sub-elite: 1.83 ± 0.08 m/s swim velocity; 618 ± 65 FINA points; and 54.91 ± 2.37 s 100 m performance best time) completed the ATM protocol described by Mason, Sacilotto, and Menzies (2011). This involved performing a modified race warm-up which focused on short front crawl sprints, followed by three free swim trials across a 10 m interval to obtain a mean maximal swim velocity. Participants were then towed in a passive state (streamline position) at their mean maximal free swim velocity. A fraction of their passive drag force was then utilised to generate an individualised fluctuating tow velocity protocol. All participants performed three maximal swim effort assisted towing trials. The assisted tow trial with the median propulsive force average was selected and the second single stroke cycle from within this trial was chosen for analysis (Sacilotto et al 2013). A singular stroke cycle was defined as one right hand entry to the subsequent right hand entry, with the same definition for a left stroke cycle. Propulsion values were calculated from the force-time profiles using the equations described by Mason, Sacilotto and Dingley (2012).
**Data Processing:** A linear length normalisation (LLN) strategy using an interpolating cubic spline was applied to normalise each curve to 100% of the stroke cycle.
***f*PCA and *bf*PCA**: For *f*PCA, B-spline basis functions were used for creation of force-time curves. These functions were smoothed using a generalized cross validation procedure and from these curves the functional principal components (*f*PCs) were derived. Each *f*PC was varimax rotated to allow for an informative evaluation of specified parts of the force-time curves (Ramsay, 2006). Each force-time curve was also weighted by each of the first five functional principal components, with resulting scalars referred to as *f*PC scores produced (Ramsay & Silverman, 1991).
**Discriminant Analysis:** *f*PC scores were assessed using stepwise discriminant function analyses (SDFA) for classification according to performance level (elite or sub-elite). The smallest Mahalanobis distance (D2) procedure was used in each case using prior allocation probabilities to account for the different sample sizes in each comparison.

**RESULTS AND DISCUSSION:** The results found were in support of the hypothesis. The type of variability described by each *f*PC is shown in Figure 2. The corresponding percentage contribution for each *f*PC to the total amount of variability in all curves are also shown in these graphs. Mean scores for *f*PCs are in Table 1. For force-time *f*PC scores, SDFA for competition levels identified scores on for *f*PC5 as having the greatest statistically significant discriminating power, exact $F = 35.480$ (degrees of freedom (*df*) $df1 = 1$, $df2 = 34$, $p < 0.001$), between groups. No other *f*PCs demonstrated statistically significant discriminating power between the two competition levels. The results of the discriminant analyses using *f*PC scores for force-time data as predictors of performance level and gender are shown in Table 1. This table shows the percentage of correct and incorrect classification for each discriminant analysis.

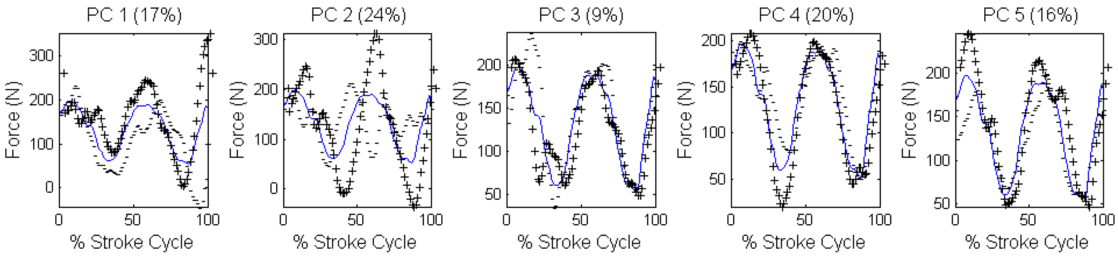


**Figure 2: In the first five *f*PCs displayed, the blue line represents mean force-time, the '+' line represents positive scorers who are +2SD from the mean function and the '-' line represents negative scorers who are -2SD from the mean function.**

**Table 1:**
**(A) *f*PCA mean (SD) scores for competition level. (B) Percentages of correct classification of *f*PCA.**

**(A) Competition Level *f*PCA scores**

| | ***f*PC Number** | ***Mean (SD)*** |
|---|---|---|
| ***Elite*** | **PC1** | 106.2 (439.7) |
| | **PC2** | 179.3 (446.6) |
| | **PC3** | 16.8 (274.2) |
| | **PC4** | 192.3 (290.7) |
| | **PC5** | 221.0 (313.9) |
| ***Sub-Elite*** | **PC1** | -166.9 (320.5) |
| | **PC2** | -281.8 (429.6) |
| | **PC3** | -26.4 (327.3) |
| | **PC4** | -302.1 (478.3) |
| | **PC5** | -347.3 (210.9) |

**(B) Gender *f*PCA - % Classified**

| | ***Elite*** | ***Sub-Elite*** |
|---|---|---|
| ***Elite*** | **86.4** | 13.6 |
| ***Sub-Elite*** | 7.1 | **92.9** |

The SDFA of *f*PC scores revealed *f*PC5 discriminated most effectively between performance levels. Positive scoring participants for *f*PC5 were characterized by an increased amplitude of force at the start of the stroke cycle and also during the middle of the stroke cycle for the second peak of force (Figure 3). As previous work using ATM force-time profiles was limited by not being able to correct for the difference in stroke frequency between swimmers, being able to compare swimmers against one another in a quantitative form has produced positive results. Given the large percentages of correct classification for both elite (~86%) and sub-elite (~93%) swimmers it is likely that the differences between positive and negative scores contribute to a more optimal propulsive force production in sprint front crawl swimming for elite swimmers. Future work using functional data analysis could be undertaken by investigating the effect of right and left stroke cycles and their potential asymmetry effect. Furthermore, insight into how a female sample compares to a male sample could also be researched.

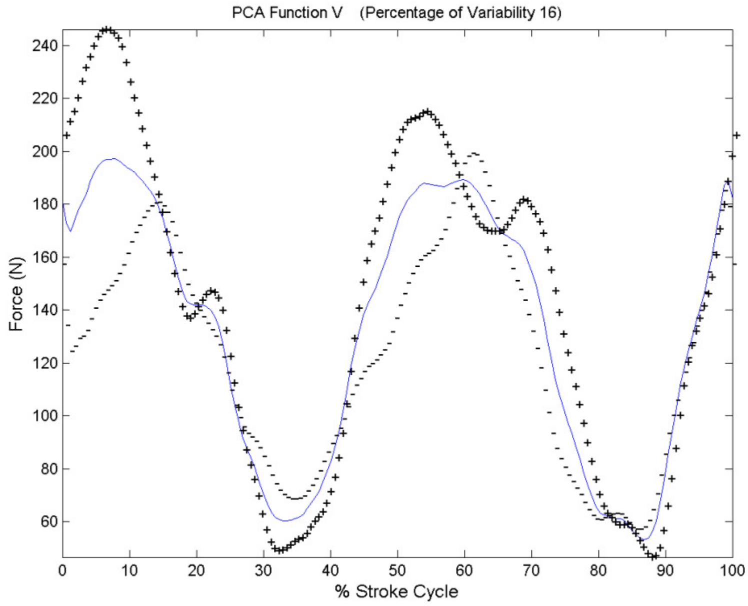


**Figure 3: Enlarged graph of *f*PC5 where elite = +; and sub-elite = -; blue line = mean of the two groups.**

**CONCLUSION:** The main findings of this investigation demonstrated that a statistically significant distinction in ATM force-time profiles can be made between elite and sub-elite male sprint front crawl swimmers. Moreover, *f*PC5 analysis revealed a more pronounced double peak profile pattern within the elite sample, which is consistent with previous qualitative assessment of the ATM force-time profiles. Future work could focus on determining what these double peaks are attributed to during free swimming and also investigate force-time profiles within a female cohort.

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