DOES THE ALIGNMENT OF THE FORCE VECTOR AND THE CENTRE OF MASS TRAJECTORY AFFECT TUMBLE TURN PERFORMANCE?

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We examined the hypothesis that the exit velocity (V_{out}) during the freestyle tumble turn depends on the alignment of the force vector with the body centre of mass trajectory. Seven swimmers performed a total of 21 turns while video and force data were gathered. We calculated the angle from the centre of pressure to the body centre of mass (COM) and determined its difference with the angle of the push-off force vector during wall contact. This difference was then correlated with V_{out}, yielding a non-significant result (-4.89 ± 2.48° with r = -0.11 (p = 0.63), thus refuting the hypothesis. However, there was a strong correlation between V_{out} and the impulse of the projection of the force vector on the COM vector (258 ± 75 N*s with r = 0.76 (p < 0.001)), which requires further scrutiny.

KEYWORDS: swimming, tumble turn, biomechanics, centre of mass, push-off force.

INTRODUCTION: The importance of the tumble turn in swimming races is well documented in the literature (Veiga at al., 2013; Morais et al., 2019a; Born et al., 2021). The freestyle tumble turn involves a series of coordinated movements aimed at minimizing transition time and maximizing velocity after the turn. Crucial to the turn is the wall contact phase: apart from the start this is the only time the swimmer interacts with a solid object. This gives the swimmer the opportunity to generate substantial velocity through a forceful push-off, typically accelerating beyond the free-swimming velocity.

The variables having the greatest influence on the tumble-turn time are the peak push-off force (Fpeak) (Blanksby et al., 1996; Araujo et al., 2010) and the Tuck Index (TI) (Blanksby et al., 1996; Araujo et al., 2010; David et al.,2022).

These variables are simplified aspects of a complex coordinated movement. The Fpeak represents the maximal amount of force exerted, but without considering its direction, while the TI does not provide information about the body's orientation in space (i.e. the same TI can be achieved with vastly different knee angles and body orientations). While these measures are useful for an initial analysis, they ignore many factors that are relevant for a successful turn. Therefore, a more fundamental approach is needed to better understand the interactions between the body and the force applied to the wall.

From a biomechanical point of view there is a critical interaction between the force direction and the body centre of mass (COM). This interaction is critical because it determines the changes in directions and orientation of an object. The interaction between the force direction and the COM has been extensively investigated in many sports and activities, including the squat jump (Luhtanen & Komi, 1978) and has been found to be a performance determining factor. However, to our knowledge there are no studies examining the interaction between the COM trajectory and the push-off force during the tumble turn.

This study aimed to fill this gap by addressing a fundamental research question: how precisely do swimmers align their force vector with their body centre of mass trajectory during the freestyle tumble turn? We hypothesized that an alignment of the force vector with the body centre of mass will optimize turn performance. If this is indeed so, this principle could be used to enhance the push-off phase, facilitating an increased velocity as swimmers leave the wall.

METHODS: For this study 7 active swimmers (3 male, 4 female) performed a total of 21 turns at maximal effort. Their age and highest FINA/WA point scores were 20.85 ± 2.27 and 814 ±

106, respectively. All turns were performed in InnoSportLab de Tongelreep at Eindhoven, the Netherlands, during which video and force data were gathered.

Video images were recorded with 2 cameras (U3-3080CP Rev.2.2, 150 Hz, IDS, Obersulm, Germany), embedded in the pool's lateral wall. The cameras were placed at a distance of 2 meters from the wall above the water and at the same distance from the wall at 0.55 cm below the surface. The video data from the cameras were acquired using the software package Streampix 9 (Norpix, Montreal, Canada, 2022). Both cameras were synchronized by an external custom-made trigger pulse generator. Custom-made software was used to calibrate the field of view of the cameras (Camera Calibration Toolbox' [Bouguet, 2008]).

The forces were recorded using a Kistler force plate (1,000 HZ, 9691 A, Switzerland) embedded in the wall at the position where the push-off forces are exerted. The force plate records all the forces applied to the plate in the horizontal direction (perpendicular to the plate) and the vertical direction (along the up downwards direction of the plate). The video and force plate data were synchronized using a LED light. To eliminate the influence of noise and waves the force data was filtered using a 20 Hz low-pass second-order Butterworth filter. Wall contact time (WCT) was defined as the time the force in horizontal direction exceeded 250 N until it dropped below 250 N again. The force data was then down sampled via linear interpolation to 150 Hz to match the frequency of the video data. From the force data, the peak push-off force, mean force and standard deviation were calculated. In addition, the vertical and horizontal components of the force and impulse were calculated from the force data. Since the vertical force had a negative portion the minimum of the vertical force was also calculated.

From the video data, the location (horizontal and vertical coordinates) of the following joints were determined on both sides of the body: ankle, knee, shoulder, hip and elbow. The coordinates were determined manually and translated to real world coordinates using Camera Calibration Toolbox in Matlab (R Core Team, 2022). These coordinates were determined from approximately 0.5 s before the first wall contact until 0.5 s after the last wall contact. With these coordinates the whole-body centre of mass was calculated using a weighted average (Plagenhoef et al., 1983). The magnitude of the velocity of the COM in the first 0.2 s after last wall contact was taken as measure of push-off performance (v_{out}). The coordinates of the centre of pressure (COP) were also extracted from the video footage and determined the origin of both the force and COM vector. With these values the angle between the horizontal and the force and COM vector and the difference between the two angles was determined. The absolute sum of the angle was calculated and normalized to the WCT to examine the discrepancy between the two vector angles. To gain insight into the efficiency of the push off, the projection of the force vector on the COM vector was calculated. With this projection the impulse used to accelerate the COM and the percentage of the total impulse used to accelerate the COM was calculated. Pearson correlation coefficients were calculated for all the outcome variables with v_{out}. The correlation coefficients were classified as low for $0.2 < r < 0.39$, moderate for $0.4 < r < 0.59$, high for $0.6 < r < 0.79$ and very high for $0.8 < r < 1.0$.

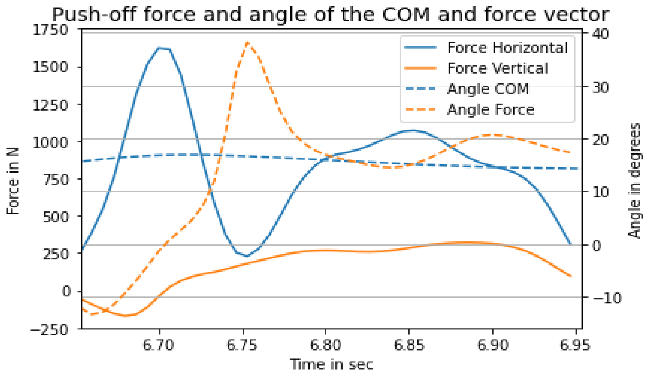

Figure 1. Plot of the push-off force components and the angle of the COM and the push-off force. The solid lines represent the forces, and the dashed lines represent the angles.

RESULTS: All turns were included. The mean v_{out} was 2.45 ± 0.24 m/s. High correlations were found between the v_{out} and the total impulse (306 ± 85 N*s with r = 0.78 (p < 0.001)) and impulse projection COM (258 ± 75 N*s with r = 0.76 (p < 0.001)). Moderate correlations were found between the v_{out} and the following variables: peak force (2211 ± 794 N with r = 0.44 (p = 0,04)), average force (1157 ± 309 N with r = 0.55 (p < 0.01)), peak horizontal force (2193 ± 796 N with an r = 0.44 (p < 0.05)), average horizontal force (1136 ± 309 N with r = 0.55 (p = 0.01)), peak vertical force (320 ± 76 N with r = 0.56 (p = 0.01)), minimum vertical force (-313 ± 100 N with r = -0.45 (p = 0.04)). No significant correlations were found between the v_{out} and the average vertical force (105 ± 34 N with r = 0.19 (p = 0.41)), the average difference in angle (-4.89 ± 2.48 ° with r = -0.11 (p = 0.63)) and the sum absolute angle per second (1204 ± 230 °/s with r = 0.02 (p = 0.94)). Both the vertical and horizontal peak force had a similar moderate correlation (r = 0.56, r = 0.55 respectively). An example of the difference between the force vector angle and the COM vector angle is shown in figure 1.

DISCUSSION: This study examined the alignment of the force vector with the body centre of mass. The results revealed no correlation between the v_{out} and any variable directly related to the difference in angle. These findings were not in agreement with our hypothesis. However, there was a high correlation (r = 0.76) between the v_{out} and the impulse projection of de force vector on the COM vector, which is contradictory to the first finding since the projection is a product of the total push-off force and the difference in angle between the two vectors. Therefore, it cannot be concluded that the difference in angle is irrelevant. Looking at the plot of the angles of the force vector and the COM it shows that at the beginning of the turn there was a larger difference between the two vectors than during the second part of the turn (figure 1). A more fine-grained analysis is needed to gain a better understanding of the interaction of the force vector on the COM throughout the wall contact time.

Peak forces, average force and horizontal peak force reported in this study were comparable with previous tumble turn studies (Lyttle et al., 1999; Silveira et al., 2011; Puel et al., 2012). The correlation between the v_{out} and the horizontal peak forces were lower than reported previously, in contrast to the correlation between the v_{out} and the vertical peak force which were higher than reported previously (Blanksby et al., 2004). This difference could be due to the fact that Blanksby et al. used age-group swimmers and reported much lower peak forces. Future research should be directed at uncovering the role of the vertical peak force in the overall turn performance. It could be hypothesised that this force serves the function of counteracting the rotation before wall contact. In addition, possible negative effects of a medio lateral force component on the turn performance should be taken into account.

The present study has several limitations. Firstly, the analysis of a complex three-dimensional movement it was reduced to two dimensions, inevitably leading to a loss of information. Secondly, looking at the whole WCT may not be the best approach. A more detailed analysis of the WCT and the actions that happen during this phase is required. Thirdly, simplifying the COM to a singular point in space and taking the same weighted averages for all swimmers may lead to an oversimplification of the COM and thus to wrong coordinates. This is especially true in view of the difference in weight distribution between men and women. Therefore, male and female swimmers need to be analysed separately in future research. These weighting factors have a large influence on the location of the COM and can thus result in difference research outcomes. This could be overcome by including segment masses in future. The determination of the coordinates of the centre of pressure should be automated in future analyses. Finally, the variation in the data was limited because all turns were performed at maximal effort. It would be advisable to include more variation at sub maximal velocities to draw conclusions based on a broad spectrum of velocities.

CONCLUSION: There was no correlation between the exit velocity (v_{out}) of the turn and the average difference in angle, or the sum of the angle over the whole wall contact time. However, when taking a close look at the plot of the different angles, a large difference was present between the vector angles at the beginning of the wall contact, while at the end of the wall contact the angles were quite well aligned. The findings of the present study stand in conflict with the biomechanical model proposed in the Introduction. Future studies should focus on the functional differences at the beginning and end of the wall contact phase. Based on the present results, it can be concluded that a more fine-grained analysis of wall contact is required to better comprehend the interaction between the force vector and the body centre of mass during the wall contact phase.

REFERENCES

Araujo, L., Pereira, S., Gatti, R., Freitas, E., Jacomel, G., Roesler, H., et al. (2010). Analysis of the lateral push-off in the freestyle flip turn. J. Sports Sci. 28, 1175–1181. doi: 10.1080/02640414.2010.485207

Blanksby, B. A., Hodgkinson, J. N., and Marshall, R. N. (1996). Force-time characteristics of freestyle tumble turn by elite swimmers. South Afr. J. Res. Sport Phys. Educ. Recreat. 19, 1–15.

Blanksby, B., Skender, S., McElroy, K., Landers, G., and Elliott, B. (2004). Swimming: an analysis of the rollover backstroke turn by age-group swimmers. Sports Biomech. 3, 1–14. doi: 10.1080/14763140408522826

Born, D. P., Kuger, J., Polach, M., and Romann, M. (2021). Start and turn performances of elite male swimmers: benchmarks and underlying mechanisms. Sports Biomech. 1–19. doi: 10.1080/14763141.2021.1872693

Bouguet, J. Y. (2008). Camera calibration toolbox for Matlab. Available at: http://robots.stanford.edu/cs223b04/JeanYvesCalib/download/index.html (accessed August 26, 2022).

David, S., Grove, T., Duijven, M. V., Koster, P., & Beek, P. J. (2022). Improving tumble turn performance in swimming: the impact of wall contact time and tuck index. Frontiers in Sports and Active Living, 4, 936695.

Luhtanen, P., & Komi, P. V. (1978). Segmental contribution to forces in vertical jump. Eur J Appl Physiol. , *38*, 181-188. doi: 10.1007/BF00430076

Lyttle, A. D., Blanksby, B. A., Elliott, B. C., and Lloyd, D. G. (1999). Investigating kinetics in the freestyle flip turn push-off. J. Appl. Biomech. 15, 242–252. doi: 10.1123/jab.15.3.242

Morais, J. E., Barbosa, T. M., Neiva, H. P., and Marinho, D. A. (2019a). Stability of pace and turn parameters of elite long-distance swimmers. Hum. Mov. Sci. 63, 108–119. doi: 10.1016/j.humov.2018.11.013

Plagenhoef, S., Evans, F. G., & Abdelnour, T. (1983). Anatomical data for analyzing human motion. Research quarterly for exercise and sport, 54(2), 169-178.

Puel, F.,Morlier, J.,Mesnard,M., Cid,M., andHellard, P. (2010b).Dynamics and kinematics in tumble turn: an analysis of performance. Comput.Methods Biomech. Biomed. Engin. 13, 109–111. doi: 10.1080/10255842.2010.495586

Puel, F., Morlier, J., Avalos, M., Mesnard, M., Cid, M., and Hellard, P. (2012). 3D kinematic and dynamic analysis of the front crawl tumble turn in elite male swimmers. J. Biomech. 45, 510–515. doi: 10.1016/j.jbiomech.2011.11.043

Silveira, G. A., Araujo, L. G., Freitas, E. D. S., Schütz, G. R., de Souza, T. G., Pereira, S. M., et al. (2011). Proposal for standardization of the distance for analysis of freestyle flip-turn performance. Revista Brasileira de Cineantropometria e Desempenho Humano 13, 177–182. doi: 10.5007/1980-0037.2011v13n3p177

Veiga, S., Cala, A., Frutos, P. G., and Navarro, E. (2013). Kinematical comparison of the 200m backstroke turns between national and regional level swimmers. J.Sports Sci. Med. 12, 730–737.

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