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Knowing what amount of tuck, as measured by tuck index, produces the highest impulse values during the push-off, along with push off phase duration and distance traveled by the center of mass during the push off phase of a squat jump, will help to optimize flip turn and overall swim performance. The purpose of this study was to determine how to optimize flip turn performance and thus overall swim performance through manipulating the amount of tuck during the push off phase of a squat jump, a task mechanically similar to the push off phase of flip turns. 28 subjects (8 male, 20 female) volunteered for this study. There were no significant differences in the impulse produced across conditions. Analysis of push off impulse duration revealed that the least tucked position produced the shortest impulse duration, with all other conditions being significantly longer. Center of mass excursion revealed the same trend, with the least tucked position necessitating the least center of mass travel and all other conditions necessitating significantly more.

EFFECT OF TUCK INDEX ON IMPULSE PRODUCED DURING A SQUAT JUMP IN SWIMMERS

by

Adam Douglas Smith

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APPROVAL PAGE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Flip Turns and Biomechanical Performance

Swimming is a popular sport that attracts people of all ages which is contested on local, regional, national and international levels. Within one swim race there are many factors which influence swim performance. Such factors include the start, arm stroke technique, kicking technique, and quality of the swimmers streamline. One final element capable of influencing swimming performance is that of the flip turn, which will be the focus of this investigation.

The flip turn is the point during swimming at which the swimmer converts linear momentum in one direction (towards the wall) into linear momentum in the opposite direction (away from the wall) through a variety of methods. The flip turn for each stroke has unique characteristics and rules which govern how and when the flip turn may be executed during a race (FINA, 2005-2009). While any turn is legally permitted in freestyle swimming, the preferred and mostly commonly used flip turn is the tumble turn. Briefly, this turn involves a modified somersault, followed by extension of the arms and legs while pushing off of the wall, in a prone position (Cox, 1981).

Within the motion of the flip turn, there are several kinetic and kinematic parameters which can affect the performance of the flip turn, and thus, the overall swim performance. Previous studies have examined the effect of impulse generation on flip turn performance and overall swim times. Early work reported that increasing the impulse generated during a turn decreased return swimming time, thus improving swim performance (Nicol and Kruger, 1979). It has also been established that impulse generation during the turn was one of several predictors for 50m swim time in males, and in females, higher impulses and faster round trip times (RTT) were recorded when their peak forces were higher (Blanksby et al., 1996b). Further, impulse has been significantly correlated with both 50m RTT and 5m RTT (Blanksby et al., 1996a). In addition, although impulse alone did not significantly add to a prediction equation of wall push off velocity; wall push-off time, another variable in impulse generation, was the best single predictor of performance (Lyttle et al., 1999). Finally, it has been reported that the impulse created during a flip turn was significantly greater than that created during a static wall push-off (Takahashi et al., 1983). Collectively these studies suggest that the ability of an individual to generate an impulse can impact swimming performance.

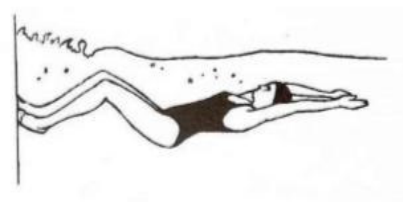
Few studies offer suggestions on how to improve flip turn performance. If sufficient force could be generated, then a strategy to flip in which the legs are straighter is preferred because the body travels less distance, minimizing time, thus improving swim performance (Blanksby et al., 1996a, Blanksby et al., 1996b). Further supporting this idea is a study that stresses an optimal body position that allows for maximal force generation while decreasing wall push-off time (Lyttle et al., 1997). The most common method of ascertaining a swimmers body position during a flip turn is through the use of tuck index, which provides a description of the amount of tuck the legs are in; this value is reported as a percentage of the original trochanteric height (Blanksby et al. 1996b).

These studies suggest that there is a link between body position and flip turn performance but do little to quantify this relationship.

The body of coaching literature related to optimal flip turn position focuses mainly on coaching "cues" to help swimmers perfect the flip turn, rather than providing empirical evidence for the specific positions in terms of joint angles, that lead to the optimal flip turn strategy (Hines, 1993; Ward, 1975, Cox, 1981; Furniss, 1984). These authors use language such as, *"a good way to determine exactly how much knee bend you need is to stand on dry land and pretend you are about to jump as high as you can.....crouch down to what feels like the optimum take-off point"* (Hines, 1993). Also, it has been suggested that the knees be relaxed and bent as they fall around for the turn (Furniss, 1984). Finally, about 90º of hip and knee flexion has been proposed as the best alignment of the lower extremity during a flip turn (Trembley, 1982). Although the coaching literature seems to allude to a best position for the flip turn, we are unable to locate literature that supports an optimal amount of tuck for the flip turn with actual biomechanical outcome data.

Developing a Land-Based Task to Measure Flip Turn Performance

In order to examine the kinetics of the flip turn, a vertically mounted, waterproof force plate is seemingly the optimal method to gather this data. In the absence of this equipment, it may be possible to model the task with a land based set-up. Figure 1 visually demonstrates that a swimmer performing a flip turn and an athlete performing a squat jump use similar lower body positioning (flexion of the lower extremity joints) to complete the task.



(A) (B)

Figure 1: Graphical representation of squat jump and flip turn.
Fig. 1A is adapted from http://www.athleticadvisor.com/images/plyo_images/squat_jump.jpg.
Fig. 1B is adapted from http://www.winderickx.com/gillis/photos/swimming/tumble_turn_crawl.jpg

The primary limitation in trying to replicate the joint positions and mechanics of a flip turn in a land-based analysis is the little to no kinematic data available for the hip, knee, and ankle in terms of joint positions during the flip turn. Thus, comparison of the flip turn mechanics to squat jump mechanics must rely on anecdotal and visual evidence of the flip turn, in comparison to data reported for the squat jump.

During a flip turn, the swimmers trunk is essentially erect exhibiting slight flexion. The amount of hip flexion will increase as tuck increases, indicating the legs are pulled further to the chest, thereby increasing the angle between the thigh and trunk segments. For three knee flexion angles (70°, 72.7°, and 90°) during a squat jump, the hips at initial push-off were at angles of 58.0°, 61.9° and 85.5° respectively (Bobbert et al. 1996, Moran and Wallace, 2007). This indicates that as the lower extremity becomes more tucked, the hips display more and more flexion. This trend is consistent with a flip turn that is performed in a more tucked position (90° as opposed to 70° of knee flexion).

The knee joint is seemingly the easiest at which to manipulate both squat depth and amount of tuck. Flip turn studies have shown that peak forces were noted at knee angles of 60° (0° being full extension) (Takahashi et al., 1983), which was consistent with a finding that peak force during a vertical (not squat) jump was recorded between knee angles of 60° and 80° (Ae, 1982). Further, the average maximum knee flexion value during a flip turn has been recorded as 59.3°, with the range being from 33° to 98° (Takahashi et al., 1983). This indicates that flip turns occur at a wide range of knee flexion values and that the knee is capable of performing this task through a large range of motion. During squat jumping, the knee joint at push-off was reported to be at 72.8°, also within the range reported during the flip turn, and very close to one of the conditions in another squat jumping study (Bobbert et al., 1996). Finally, it should be noted that the squat jump knee flexion values of ~70° are similar to the flip turn knee flexion value of 59.3° reported by Takahashi et al., 1983, and fall well within the reported standard deviation of 22.8°.

We were unable to locate data on ankle plantar flexion values during the flip turn. Anecdotal experience strongly states that the feet are never placed flat against the wall during a turn, and that some plantar flexion is necessary to push off of the wall appropriately (Lyttle et al., 1999). For the squat jump, the ankle flexion angles have ranged from 68.8 – 75.6° (Bobbert et al., 1996, Moran and Wallace, 2007. The ankle does experience some flexion in both tasks, although the quantity is not well established for direct comparison of squat jumping and flip turning.

Collectively it appears as though the lower extremity segments experience many of the same ranges of motion between squat jumping and flip turning. Thus the squat jump is seemingly a mechanically similar alternative to the flip turn; permitting land based analysis of many of the same factors important to flip turn mechanics.

Maximizing Performance

Evidence in the squat jumping literature supports a lower extremity position(s) that optimizes jumping kinetics (Domire et al., 2007; Selbie et al., 1996, Zhang et al., 2000). From the collective results of these studies, it is evident that manipulation of the knee joint flexion angle impacts the kinetic output which is also important in a flip turn. Specifically, it has been reported that, there was no difference in jump height when jumping from a preferred squat depth and a deeper squat depth characterized by greater knee flexion angle (Domire et al., 2007). Push-off time during the same study was also found to increase significantly as squat depth increased (Domire et al., 2007). Thus the "preferred" squat depth would be beneficial in flip turning as it produced the same result (vertical jump height) while push off time was minimized (thus improving swim time). In a study that modeled the squat jump, simulated vertical jumps from 125 different starting positions derived from different initial angular positions of the ankle, knee, and hip generated multiple positions that produced the same vertical jump height (Selbie and Caldwell 1996). However, data were not presented that described these positions in terms of specific joint angles. This is important because if there are multiple positions that produce the same outcome, coaching an athlete into this position will be easier.

In a task such as squat jumping, the extent to which the person can attain maximal performance largely depends on coordination of the musculoskeletal system; the optimal coordination pattern for each individual may be found through practice (Bobbert and VanSoest, 2001). At a deeper than preferred squat depth, individual coordination of the jump is reduced (Domire and Challis, 2007). Squat jumps from a deeper than preferred squat depth have been reported to require more effort when compared to a jump from a preferred height as well as an increase in time that it takes to perform a deeper squat (Domire and Challis, 2007). However, it was hypothesized that if the deep squat position was practiced, it could then become the subjects "preferred" depth, indicating that neuromuscular training may play a role in the optimization of squat jump kinetics (Domire and Challis, 2007). Overall this suggests that there is a lower extremity position, specifically an amount of tuck that produces optimal kinetic results in a jumping task, which is functionally similar to a flip turn push-off.

Statement of the Problem

Currently, there is no data available that presents how kinetic outcomes change as kinematic variables are manipulated (specifically the total amount of flexion of the lower extremity) for the flip turn. Finding the amount of tuck, or range of flexion angles, at which the maximum impulse is generated will allow for more effective coaching in flip turn technique, especially among elite athletes for whom tenths of a second could mean the difference between placing first and placing tenth.

Because of the similarities in the positioning of the flip turn push off and the squat jump, the present study will attempt to establish relationship between lower extremity tuck and impulse generation, push of impulse duration, and center of mass excursion. To best examine the differences, the impulse that is generated, as well as the push off phase duration and distance traveled by the center of mass at each lower extremity position will be compared to find the position that produces the optimal solution in a swimming context.

Purpose Statement

The purpose of this study is to determine the relationship between squat depth and particular variables that are of interest when evaluating swim performance. Knowing what amount of tuck, as measured by tuck index, produces the highest impulse values during push-off, along with push off phase duration and distance traveled by the center of mass during the push off phase of a squat jump, will help to optimize flip turn and overall swim performance.

Hypothesis Statements

Objective 1 – Determine the amount of tuck necessary to maximize squat jump performance

Hypothesis 1 - As tuck index increases or decreases from the tuck index at a subject's preferred squat depth; the impulse generated will decrease.

Objective 2 - Determine the amount of time necessary to complete the push off phase of the squat jump.

Hypothesis 2 – The push off impulse duration will be shortest at the least tucked position and will increase as the squat position becomes more tucked.

Objective 3 - Determine the amount of distance that the center of mass must travel during the push off phase of the squat jump performance.

Hypothesis 3 – Center of mass excursion during the push-off phase will increase as a more tucked position is assumed. The rationale for this hypothesis is to quantify in linear terms the change in center of mass excursion across different squat depths and find the position in which the center of mass travels the least.

Operational Definitions

Impulse - Defined as the product of a force times the period of time over which the force is developed. The time period used in this study will be the time at which vertical ground reaction force increases following the squat (indicating the start of push-off) by the subject to the time at which zero vertical ground reaction force is measured (indicating take off from platform). The force generated during this period will be recorded in Newtons and multiplied by the time (Ns).

Tuck Index - The amount of tuck in swimmers legs as they push off of the wall following a flip turn defined as a ratio of trochanteric height during the flip turn to original trochanteric height (Blanksby et al., 1996b). Trochanteric height is simply the height from the superior aspect of the greater trochanter of the femur to the floor (or wall as the case may be). A larger tuck index indicates a more extended position.

Swimmer - Defined as someone who can complete two consecutive lengths of a standard pool (50 yards or meters) and do a flip turn between the lengths.

Squat Jump – A task in which the subject will squat down to a given distance by flexing the knees, hold this position for a period of time, and then perform a maximal effort vertical jump (Moran and Wallace, 2007).

Push Off Impulse Duration – The time segment for which the impulse will be calculated. Spans from the time point at which the force equals body weight + 5N to the point at which it crosses 0N.

Center of Mass Excursion – Center of mass excursion refers to the amount of vertical displacement as measured by the difference in original trochanteric height and condition trochanteric height, (i.e. tuck index). This center of mass has been established to be located at the level of the second sacral vertebrae, and, by mechanical connection at the hip joint, the greater trochanter of the femur provides a reasonable estimate of the center of mass (Saunders et al., 1953).

Limitations

The major limitation of this study is that it attempts to describe kinetics in an aquatic environment with a land-based set-up. This ignores the obvious effect that buoyancy and drag will have on the variables measured.

Delimitations

Subject Population

For this study, the subject population will be delimited to a convenience sample of swimmers (age = 18-36 years) in the local community. Subjects must also fit the operational definition of a swimmer so as to control the subject pool.

Hip Flexion

Trunk position will not be quantified directly. Assurances are made in the methods to help maintain the swim specific upright trunk position. In addition to verbal instructions to keep their chest up as straight as possible, and a demonstration of what is correct and not correct, a plumb line was hung from the ceiling in front of the subject with the instruction to, “keep everything happening in front of the string”.

Plantar Flexion

Although the amount of plantar flexion that the ankle is in during a flip turn has not been previously quantified, anecdotal evidence suggests that there is some degree, albeit small, of plantar flexion upon foot contact during a flip turn. The present study did not constrain plantar flexion in any way.

Ground Reaction Force Components

For the purposes of this study, only the vertical ground reaction force will be used. However, it is clear that during a flip turn, there is some rotation of the body that takes place. It has been demonstrated that following a push off, the horizontal (vertical on land) reaction force is the main contributor to the push off forces, and that the others (medial/lateral, anterior/posterior, and rotational) are less, with the exact significance of this decrease not being established (Walker, et al., 1995).

Countermovement during Squat Jump

It is feasible the squat jump may allow for countermovement action of the quadriceps muscles and therefore does not accurately simulate the flip turn motion in which the center of mass does not move toward the wall once the feet are planted. The squat jump, being performed from a semi-squatting position with no preparatory flexion of the joints, and therefore utilizing no eccentric loading, exhibits a lack of significant negative mechanical work being done at any of the lower extremity joints as compared to the countermovement jump (Moran and Wallace, 2007). Although subjects displayed some negative work done during the squat jump, previous work demonstrated this to be a negligible contribution to overall jump performance when compared to countermovement jumps (Moran and Wallace, 2007).

CHAPTER II

REVIEW OF LITERATURE

In order to fully understand this problem it is necessary to examine the relevant literature. First, the literature that presents the preferred flip turn strategy will be presented. Following this, a description of how to quantify one measure of flip turn performance, tuck index, and its implications on flip turn performance will be presented. Next, the relationship of impulse and swim performance will be established. Finally, jumping literature will be presented that supports a position of optimal performance and will serve as the backbone for the rationale of the present study.

Establishing Optimal Flip Turn Strategy

The first evidence that attempts to identify a preferred or optimal flip turning strategy was compiled by Ward (1975) in which 14 subjects performed pike flip turns and tuck flip turns. Results indicated that the tuck flip turn was faster, as measured by time, than the pike turn in all three phases of the turn (in, out, and total time). This indicated that a tucked flip turn position is preferred over the pike turn. It is important to note that the flip turn is the most widely used turning method in competitive swimming today. Further practical evidence for an optimal flip turning strategy comes from coaching literature. It centers on tips for coaches to get the swimmer into the best position for a flip turn.

A brief summary of some coaching points for flip turns suggests that swimmers master the "flip and roll", a process by which they approach the wall, tuck the body and perform a forward somersault into a face down position with the feet on the wall, and push off in a prone position (Cox, 1981). In an article with many real-time still photographs, the flip turn is described as a tuck and flip that should feel like a natural continuation of the swimming motion. The illustrations show that the knees are in a relaxed and slightly flexed position from which the swimmer will push off of the wall. It is noted that a common mistake is to slap the water with the legs, which means that the legs are not tucked; as a result, the importance of keeping the legs tucked close to the body during the flip is stressed. This positioning is shown in Figure 2 (Floyd, 2007).

Figure 2: Real-time still photograph of the flip turn.
Adapted from Floyd, R.T. (2007). *Manual of structural kinesiology.* New York, New York: McGraw Hill.

In an article written for Masters swimmers, some of the common flaws in flip turns are described in comparison to an efficient turn. One of the most evident differences in the two turns presented is that when the feet are planted on the wall in an efficient turn, the swimmer is already partially crouched and that when foot contact occurs, the swimmer is already “jumping” off of the wall. In the poor flip turn, the legs are nearly straight and the swimmer must crouch down once foot contact occurs. This can take significantly more time than the efficient turn (Hines, 1993).

Finally, in a review of both freestyle and backstroke starts and turns, tips for flip turn coaching are presented. It was suggested that sprint freestyle swimmers should be in about 90º of hip and knee flexion during the turn. It was also noted that many inexperienced swimmers tend to flip too close to the wall and tuck too much (Trembley, 1982).It is clear that the coaching literature stresses the importance of tucking the legs to some extent during the flip turn. It is also clear that the same literature does not attempt to quantify the amount of tuck in which the swimmer should attain.

Explanation of Tuck Index

The measure of tuck index has been used in several studies to quantify the amount of tuck present in swimmers legs during a flip turn. It has been measured as, “the point when the hip was at its minimum distance from the wall, expressed as a percentage of the trochanteric height”, with trochanteric height being measured from, “ground to superior border of greater trochanter of femur” (Blanksby et al, 1996b). This measure is also used in a study of backstrokers, who utilize the same flip turn motion as freestylers, and is defined as, “the distance of the greater trochanter of the femur from the wall at foot contact, divided by the actual trochanteric height” (Blanksby, 2004).

Performance Implications of Tuck Index

The concept of tuck index as a measure of lower extremity alignment during a flip turn has implications on the performance of both the flip turn as well as the total swimming task. In a sample of age-group swimmers, a mean tuck index of 56.6 $\pm$ 17.2% was recorded (Blanksby, 1996a). For these same swimmers, this tuck index was significantly correlated to time spent on the wall during the flip turn, peak force generated, and 2.5, 5.0, and 50m RTT. This is interpreted as when the swimmers' legs get straighter (i.e. less knee flexion), the flip turn times get faster. This result is supported by the data for the fastest and slowest thirds of the sample, using 5m RTT as the dependent variable. It demonstrated that the fastest third had a higher, although not statistically significant, tuck index than the slowest third, these values were 62.7 $\pm$ 19.1% and 49.3 $\pm$ 15.6% respectively. It was concluded that there is a position where the combination of distance from wall, time spent on the wall, and force exerted on the wall are optimal. A swimmer with a tuck index of 100% cannot generate sufficient force because his or her legs are completely straight, while a swimmer with a very small tuck index spends too much time pushing off of the wall (Blanksby 1996a). Finally, the negative correlation with tuck index and the three RTT measures suggests that a swimmer who flips with straighter legs covers less total distance with their swimming than does a swimmer who flips with more flexed legs. This association is stronger as the RTT distance decreases, suggesting that the turning component represents a higher fraction of the total swimming time, stressing the importance of optimized flip turn performance (Blanksby, 1996a).

Further evidence for performance implications of tuck index is evidenced in a sample of national level swimmers. It was found that a decrease in 2.5m RTT was related to a higher tuck index, agreeing with the previous study (Blanksby, 1996a). In addition to 2.5m RTT, tuck index was significantly correlated to the peak force generated. This begins to establish the link between the position of the lower extremity and the kinetic outcomes of the flip turn. Tuck index was also found to be the sole independent variable in a prediction equation for 2.5m RTT time in males. The relationship between a higher tuck index and faster RTT measures agrees with the prior study by supporting the idea that as the legs are straighter during the turn, less distance is covered by the swimmer, creating faster turns (Blanksby, 1996b).

Finally, in a study of backstrokers (n=36), it was established that a tuck index averaging 60% was negatively correlated with wall contact time and positively correlated with peak force (Blanksby, 2004). It is important to note that although backstroke was the focus of this study, the flip turn motion is essentially the same as a freestyle tumble turn except that the swimmer must rollover into a prone position before executing the turn (Blanksby, 2004). In putting together regression equations to predict 5m RTT, it was found that a collection of variables, including tuck index and collectively named "force preparation", yielded better turns when the legs were straighter, peak force was high, and wall contact time was low (Blanksby, 2004).

The results of these studies show the importance of tuck index, and thus lower extremity position, in flip turn performance. Finding the optimal position and being able to reproduce it will be an essential component for effective flip turning.

Impulse Generation

The freestyle flip turn is executed at the end of a length of swimming and requires the swimmer to generate momentum in a linear fashion from a zero starting velocity. This is accomplished by generating an impulse against the wall.

The relationship between impulse and momentum can be described using Newton's second law which states:

$$\Sigma F = ma$$

Because acceleration is defined as the change in velocity divided by the change in time, the quantity ($\Delta v/\Delta t$) can be substituted for "a" in the above equation. This substitution yields the following equation:

$$\Sigma F = m\ (\Delta v/\Delta t)$$

By multiplying both sides of this equation by Δt, the equation becomes:

$$\Sigma F\ (\Delta t) = m\ (\Delta v)$$

This is known as the impulse-momentum relationship, with the left side of the equation representing the impulse, and the right side of the equation representing momentum; this means that the generation of an impulse causes a change in momentum (McGinnis, 2005). It is easy to see that manipulations of force, time, mass, and velocity will all impact this relationship and the subsequent momentum generated by the impulse. One may induce a higher impulse, and therefore higher momentum change, by producing a higher force in a fixed amount of time, or increasing the amount of time over which a fixed amount of force is produced. In relation to swimming, the goal is to keep time at a minimum so manipulations to maximize force generation are very important.

Performance Implications of Impulse

The horizontal impulse generated during a flip turn push-off has been widely established across different skill level of swimmers as well as for different swimming strokes. Within the impulse-momentum relationship, it can be seen that changes in force, time, and velocity will impact the impulse generated. Theoretically, increases in force, decreases in time, and increases in velocity would indicate faster swimming performance, so this section will be limited to impulse generation during a tumble turn and these variables are related.

Description of Impulse and Force during Freestyle Flip Turn

Although there is a relative paucity in the available literature that reports values in swimmers for peak force and impulse associated with the freestyle flip turn, several key studies reveal that there have been a wide range of peak forces and impulses reported. Subject populations of varying size, gender, and skill level have been examined which could possibly explain some of the conflicting results. Further explanation for these differences could be found in the fact that the task in these studies, although a flip turn in all of them, is different, with some values being reported for a full 50m swim, while others are only for a 15m round trip. Finally, improvements in data collection over the years may have improved the accuracy of the data in more recent studies. For a summary of these data, please refer to Table 1.

Study	Subjects	Peak Force (N)	Impulse (Ns)
Nicol et al., 1979	5 trained university swimmers	*Not Measured*	217 + 28
Takahashi et al., 1983	6 adult males (3 trained, 3 untrained)	1390 + 440	262.7 + 53.8
Blanksby et al., 1996a	36 age group swimmers	693.4 ± 228.1	177.2 ± 50.2
Lyttle et al., 1997	3 national and international male swimmers	1345.29 + 236.45	247.3 + 29.02
Lyttle et al., 1999	30 experienced male swimmers	1189.6 + 246.0	204.0 + 54.9
Blanksby et al., 2004	36 age group backstrokers	229 +70	55.6 + 12.6

Table 1: Peak force and impulse for flip turn from selected studies. All data are presented as mean ± standard deviation.

Correlation between Force and Impulse and Swimming Time

It is understood that there is a connection between ideal flip turn mechanics and improvement in swimming time. A prediction equation using return swimming time as a predictor of horizontal impulse found that increasing the impulse by 100Ns decreased return swimming time by 0.3s (Nicol et al., 1979). While this amount of time may seem insignificant, tenths of a second can be the difference between the top 8 finishers in any given swim event.

Peak force and impulse have been found to be negatively correlated with 5m RTT, indicating that as a larger peak force and impulse are generated, flip turn time is decreased (Blanksby et al., 1996a). A comparison among faster swimmers and slower turners revealed that the faster swimmers produced an impulse and peak force of 185.5 ± 52.6Ns and 805.0 ± 223.67N respectively, while the slowest swimmers produced values of 160.69 ± 26.88Ns and 548.48 ± 167.2N respectively for the same variables. The difference between the peak forces was significant but the difference in impulses was not (Blanskby et al., 1996a). It should be noted that while the impulse differences were not significant, there was a trend of lower kinetic values for slower swimmers. Finally, a regression equation to predict 5m RTT showed that peak force was the single best predictor, suggesting that there is a need to increase the impulse which results from an increased peak force applied to the turning surface, but decrease the amount of time in contact with the wall (Blanksby et al., 1996a).

Even in research that reports relationships between flip turn kinetics and round trip times with no specific impulse reported, it has been found that peak force and impulse were not found to be significantly correlated to 2.5m or 5.0m RTT in males. Females did however demonstrate significant correlations between peak force and impulse at 2.5m and 5.0m RTT (Blanksby et al., 1996b). In males, impulse was the only significant predictor variable in a regression equation for 50m RTT; for the females, 5m RTT was predictive of 50m RTT. This is interesting because both peak force and impulse were correlated to 5m RTT time, but not 50m RTT (Blanksby et al., 1996b). Finally, wall impulse has been found to be associated with lower 50m, 5m, and 2.5m RTT in backstrokers (Blanksby et al., 2004).

Correlation between Force, Impulse and Velocity

Another way to quantify the effect of flip turn kinetics on swim performance, as opposed to examining swim times, is to examine the speed of the swimmer as they exit the turn. A positive correlation between peak force and post-flip turn speed has been established, suggesting that swimmers, who push off of the wall harder, are resuming swimming at a faster velocity, thus gaining an advantage from the flip turn (Blanksby et al., 1996a, Blanksby et al., 2004, Lyttle et al., 1999). Impulse has also been positively correlated to wall exit velocity in backstrokers (Blanksby et al., 2004). It has been suggested that this peak force should be both developed gradually and be accompanied with proper body form (streamline) in order to prevent appreciable amounts of drag from occurring and swim velocity to be maximized (Lyttle et al., 2004).

Relationship between Flip Turn Kinetics and Knee Joint Angle

Evidence supporting the link between knee joint angle and changes in the kinetics of the flip turn is sparse, but a relationship has begun to be established. In a study comparing a flip turn to a static wall push, each of 6 male swimmers performed three glide starts (static push from wall) and three flip turns. The maximal flexion angle of the knee during the two motions, glide and flip turn, was 52.3 º and 59.3 º respectively (Takahashi et al., 1983). Although the difference was not statistically significant, this result may be attributed to the high standard deviation of the trained swimmers maximal knee flexion angle (22.8 º). While the relationship between knee flexion angle and impulse was not established, a trend was noticed that the trained swimmers who utilized a greater flexion angle also produced a higher impulse. Additionally in the glide condition, greater initial velocity was significantly related to higher impulse generated. This result was expected to extend to the flip turn condition as well, although data for this condition were not measured (Takahashi et al., 1983). The final important observation is that the peak force occurred at roughly 60º of knee flexion, suggesting an optimal positioning of the leg during push-off (Takahashi et al., 1983). Collectively, examination of this work reveals that both body positioning, as measured by tuck index, and force production capabilities of the swimmer can both have impacts on flip turn performance and the swim event as the whole.

Relationship of Squat Jump to Flip Turn Push-Off

In order to study the mechanics of a flip turn in the absence of a pool mounted force plate, recreating the position of the swimmer is essential, and may allow for land-based comparisons to be made. The coaching literature has stated *"a good way to determine exactly how much knee bend you need is to stand on dry land and pretend you are about to jump as high as you can.....crouch down to what feels like the optimum take-off point"* (Hines, 1993). There is a lot of literature available that examines the impact of lower extremity positioning on jump performance, and these same positions may be the positions in which simulated flip turn performance is optimal.

Influence of Squat Depth on Jump Height

In a comparison of jump height from initial squat positions of 70°, 90°, 110°, and 130° of knee flexion, it was found that jump height was significantly higher between 110° and 130°, 90° and 110°, but not 70° and 90° (Zhang et al., 2000). In contrast to these results, jump height was found to be the same in subjects jumping from a preferred squat depth and a self-selected position deeper than the preferred (Domire et al., 2007). The angles corresponding to the preferred and deeper positions were 74.7 + 10.3 ° and 93.8 + 16.0 ° respectively (fully extended knee = 0 °) (Domire et al., 2007). This indicates that adjusting knee angle can impact the jump height, but inconsistency in results prevent any generalizations from being formed. The primary reason for these contrasting results is that it has been suggested that a subject's ability to coordinate the jumping movement may affect their ability to produce force across the range of motion, and thus, may explain why the subjects were not able to jump higher from the deeper squat position (Domire et al. 2007).

Influence of Squat Depth on Jump Time

Because time is a factor in both impulse generation as well as swim performance, it is important to examine the effect of knee joint angle manipulations in the time it takes to perform a squat jump. It should be assumed that faster jumps would correspond to better swim performance. Across four jumping conditions (knee angle of 130º, 110º, 90º, 70º), lower values for time of extension were recorded as the knee angle value became greater (complete extension was defined as 180º) (Zhang et al., 2000). This indicates that as the knee becomes more extended, jump time decreases. This lower time is achieved by sacrificing force production (Zhang et al., 2000), which could be necessary in terms of swim performance. It may not be necessary to produce as much force if the sacrifice is time. Further support for this trend is that jumping from a deeper squat than preferred resulted in a change of jump time from 0.30 ± 0.07s to 0.47 ± 0.07s, a significant difference. This trend of lower times with more extended knees is supported by the results that indicate that wall contact time decreases as the tuck index of swimmers becomes closer to 100% (Blanksby et al. 1996a, Blanksby et al., 2004).

Influence of Squat Depth on Force Production

In order to further the comparison of the squat jump to the flip turn push-off, an examination of the force production characteristics of different squat depths is necessary. As squat depth increases, a significant increase in average force production across four different squat depths has been established (Zhang et al., 2000). This is noted to occur inversely to the time needed to produce this force; hence, if more time is used, as in the deeper squats, less force is produced (Zhang et al., 2000). This trend is also noted in swimmers where a tighter tuck (deeper squat) may be ineffective in producing force because the swimmer must produce that force throughout a larger range of motion (Blanksby et al., 1996a).

Further, in a comparison of a preferred squat depth to a deeper squat depth, it was found that, despite similarities in the joint moments of the hip, knee, and ankle, the timing of these moments relative to take off was different at each joint, with the deeper squat depth displaying a peak moment that was further away from take off. This lends support to the idea that a "non-preferred" squat depth is not as optimally controlled (Domire and Challis, 2007).

Influence of Squat Depth on Impulse generation

The support for squat depth increasing or decreasing the vertical impulse in a squat jump is essentially non-existent. Most of the literature focuses on other kinetic variables other than impulse (Zhang et al., 2000, Domire et al., 2007). While the raw data from these studies would allow for impulse to be calculated, a much easier way to examine the effect of squat depth on impulse generation would be to shift the focus to a vertical jump task, which includes a countermovement, making it a unique task from the squat jump in which the starting position is held. The problem with this approach is that there are almost no articles that directly examine the effect of squat depth in a vertical jump and its relation to impulse. One piece of evidence that may support this relationship is that in a countermovement jump with an arm swing, the body was lowered 3cm more when compared to a countermovement jump without the arm swing. The resulting vertical impulse for the jumps was higher with the arm swing. This indicates that a lower body position produces a higher impulse (Harman et al., 1990).

A possible explanation for the lack of evidence of this trend could be that there is some debate over whether or not impulse is an appropriate measure to be used with vertical jumping. Canavan and Vescovi have established that power should be used as the standard for vertical jump comparisons as opposed to impulse (2004); this assertion has been disputed among experts however (Winter, 2005; Canavan and Vescovi, 2005). Further work to validate impulse as a reliable measure to use for vertical jumping tasks would be necessary in order to bridge this gap in the literature.

Despite this lack of agreement about the role of impulse in vertical jumping and its relation to squat depth, impulse is used in the current study because of its relevance to the flip turn, and the importance of impulse generation in terms of flip turn performance.

Optimal Jumping Strategy

Jumping literature has supported an "optimal" position for jumping based on factors such as time and force production capability. In a scenario where jump height remains unchanged, but the time required to produce that jump height is shorter (less knee flexion), the preferred squat depth, measured as 74.7 + 10.3 ° could be considered optimal (Domire et al., 2007). It has also been suggested that the optimal combination of force and time occurs at a knee angle of 90 ° (Zhang et al., 2000). Further, a simulation study of the squat jump revealed that, for 125 different starting postures, the knee explored a range of 1.41 + 0.13 radians (80.8 + 7.45 °), although the actual values of this range were not reported (Selbie et al., 1996).

From the results of these studies, it can be seen that altering the knee angle can have an impact on kinetic outcomes in a squat jumping task/position. Because there are many similarities in the flip turn push-off position and the squat jump position, the squat jump may be a suitable alternative to actual flip turns. The jumping literature supports, with actual kinematic data, the positions of the knee which produce the best kinetic results.

In summary, the position of the lower extremity during a flip turn, as measured by tuck index, has the capability to impact flip turn performance by decreasing the distance covered by the swimmer. Further, kinetic changes can improve flip turn performance by decreasing swim time as well as by increasing swim velocity. In order to establish the position in which these variables are optimized for swim performance, a squat jump task can be used due to similarities in the task. Squat depth has been shown to have an impact on jump height as well as other kinetic measures. It would appear that modifying the amount of tuck a swimmer has, through changing squat depth during a jump, can identify the best position for a swimmer to be in during a flip turn.

CHAPTER III

METHODS

Subjects

Twenty-eight subjects, 8 male, 20 female (age=23±4 years, mass=71.8±13.2 kg, trochanteric height=91.0±5.7 cm, 50 yd sprint time=35.4±12.8 seconds) volunteered for this study. Inclusion criteria were that they must be a swimmer as defined by this study (can complete two consecutive laps and perform a flip turn) and be free of lower extremity injury for at least six months prior to testing to ensure proper limb function. All subjects signed an informed consent form and complied with regulations of studies using human subjects as set forth by the University of North Carolina at Greensboro.

Instrumentation

A Kistler force plate (Kistler Instrument Corporation, Amherst, NY) interfaced with a PC via an analog to digital board was used to gather vertical ground reaction force data at 1000Hz using LabView Software. A standard goniometer quantified the amount of knee flexion at each condition.

Experimental Setup

The set-up for this experiment included a squat depth controller consisting of two standards with adjustable ledges across which bar was suspended. Measuring tapes behind the adjustable ledges on the standards ensured proper positioning across conditions. This device was placed behind the force plate so that as the subject squatted down, their backside came to rest on the wood, indicating that proper squat depth had been achieved. A plumb line was hung from the ceiling and adjusted to be about 20-25cm from the subject's chest to control trunk flexion. A representation of the experimental set-up is provided in Figure 3. This device helped to ensure the reliability of subject position across multiple trials. Intraclass correlation coefficients (3,1) are presented in Table 2. Reliability was established by familiarizing 5 subjects with the 5 different squat depth conditions and measuring their trochanteric heights and knee flexion angles during three separate trials at each condition.

Variable	ICC (3,1)	SEM
Preferred TH(cm)	0.99	1.04
73.8 % TH(cm)	0.98	1.68
62.7% TH(cm)	0.97	2.54
56.6% TH(cm)	0.96	1.01
49.3% TH(cm)	0.98	1.57
Preferred KFA(°)	0.99	0.32
73.8% KFA(°)	0.93	0.61
62.7% KFA(°)	0.44	0.59
56.6% KFA(°)	0.84	0.56
49.3% KFA(°)	0.77	0.31

Table 2: ICC and SEM Values for Trochanteric Height (TH) and Knee Flexion Angle (KFA)

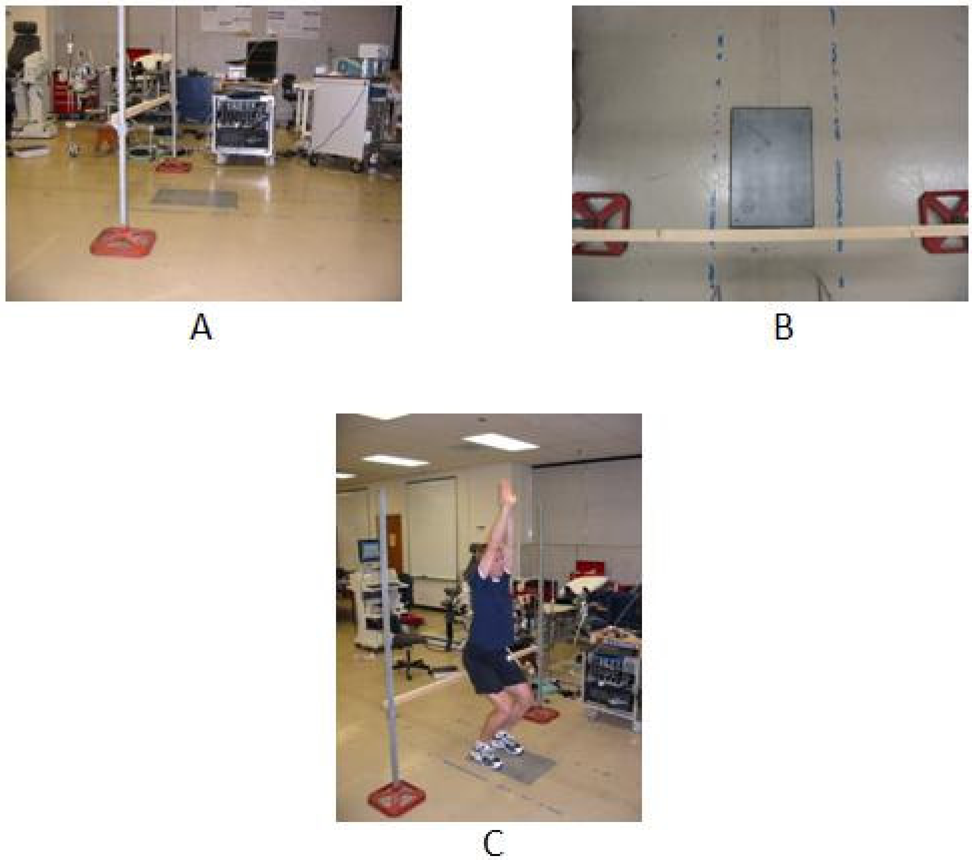


Figure 3: Experimental setup. A: Anterolateral view. B: Top view. C: Anterolateral view with subject.

Testing Procedures

Subjects were asked to wear comfortable athletic clothing which did not limit their ability to flex their knees or assume a squat position. Shoes and socks were removed for all trials in order to more accurately mimic the attire of swimmers performing a flip turn. Spandex shorts were worn to accurately maintain the point of reference (greater trochanter of right leg).

Familiarization Session

In order to familiarize the subjects to the task and the testing environment, each subject underwent a separate familiarization session between 1 and 7 days prior to data collection.

Prior to any measurements, markers were placed on the subject's right greater trochanter, right lateral malleolus, and right knee joint line. These markers helped to measure trochanteric height and knee flexion angle during familiarization. To begin the familiarization session, the subjects' trochanteric height was established by measuring the linear distance from the superior aspect of the greater trochanter of the right leg to the floor (Blanksby et al., 1996b). The trochanteric height needed for each condition was established by multiplying the tuck index as a ratio by the original trochanteric height and recorded.

The following tuck indexes were used as conditions: 73.8%, 62.7%, 56.6%, and 49.3%. Again, smaller tuck index is suggestive of a more flexed position. The latter three tuck indexes were chosen as they were the three measures attained in a study that ascertained the tuck index of the fastest and slowest swimmers as well as the average tuck index for the group, and the highest tuck index represents the tuck index at +1SD from the mean of the group (Blanksby et al., 1996a). One final tuck index, corresponding to the trochanteric height at the subject's preferred squat depth, was used.

For each of the five conditions, the subject first obtained their proper foot position through a practice squat. Next, trochanteric height was measured simultaneously as the subject squatted to the bar. The measured value of trochanteric height was compared to the desired trochanteric height for the condition; precision of $\pm$0.5cm was established. The squat depth controller was adjusted up or down in order to reach the desired trochanteric height for each desired tuck index. Once the squat depth controller was at the correct height, the subject was instructed to squat back down to the bar so that knee flexion could be measured. Finally, the subject was given three practice jumps, after instruction on the commands for jumping. The commands were as follows, “place your feet, arms up, chest up tall, everything happening in front of the string, squat down, pause, pause, JUMP!” The total length of the pause was less than two seconds. Subjects were instructed to land back on the force plate with both feet in order to prevent any lateral or anterior/posterior displacement and allow for a vertical impulse to be gathered. Attention was paid to the ability of the subject to reach the required squat depth and hold for the proper amount of time.

Testing Session

For the data collection session, subjects were permitted to wear whatever clothing they wanted, provided that it did not hinder their ability to squat to each depth. Before the subject arrived at their data collection session, trial order was randomized to help prevent any learning effect and to minimize systematic fatigue and the first depth was set based on the measurements taken during familiarization.

For each condition, the subject was given a few trials to re-familiarize themselves with the apparatus and the task. Following this, three successful trials were recorded and the subject was allowed ~2 minutes of rest to allow for repositioning of the squat depth controller to the next depth. A successful trial was defined as squatting to appropriate depth, holding at that position for the required amount of time, jumping from that position with no countermovement, and landing back on the force plate with both feet. Further, an unsuccessful trial displayed a significant (on visual exam) countermovement in the force-time recording. This appeared as a downward dip in the force curve immediately preceding the push off phase of the jump. The subjects were instructed to jump using the same commands given to them during familiarization.

Data Reduction

Raw kinetic data was low pass filtered at 60 Hz using a zero lag Butterworth digital filter. For each trial, a force-time curve was constructed. In order to capture the push-off phase of the squat jump, the portion of the graph representing the push-off was used. The push-off phase was defined as when the vertical ground reaction force exceeds body weight by 5N to the point when the vertical ground reaction force equals 0N (Jensen and Ebben, 2002). Impulse (Ns) was calculated from this portion for each trial. Average push-off impulse across the three trials for each condition was calculated and used for statistical analysis. For a description of push off impulse, please refer to the operational definition in Chapter 1. Center of mass excursion was determined by subtracting the condition trochanteric height from the original trochanteric height.

Statistical Analysis

Hypothesis 1 – Impulse generation

A repeated measures ANOVA compared the impulse generated during the squat jump across each condition.

Hypothesis 2 – Push off impulse duration

A repeated measures ANOVA compared the impulse duration (time segment from which the impulse was calculated) for the squat jump across each condition

Hypothesis 3 – Push off phase center of mass excursion

A repeated measures ANOVA compared the amount of distance the center of mass must travel during the squat jump at each condition. Again, this distance represents the difference between the original trochanteric height and the trochanteric height at the condition.

All significant differences will be subjected to pairwise comparisons to establish which conditions are significantly different from each other. Significance was set a priori at P=0.05 and SPSS for Windows was used for all statistical analyses.

CHAPTER IV

RESULTS

Impulse Generation

The repeated measures ANOVA revealed no significant difference across squat jump conditions ($F_{(4,108)} = 0.474$; $p = 0.755$). The mean impulse and standard deviation for each condition are presented in Table 3. Representative force/time histories for each of the set tuck indexes are presented in Figure 4.

Tuck index (%)	**Mean ± SD (Ns)**
Preferred (64.6)	141.7 ± 37.8
73.8	143.0 ± 38.0
62.7	142.8 ± 39.5
56.6	141.4 ± 40.3
49.3	142.9 ± 40.0

Table 3: Mean impulse data for each condition. * denotes significance from preferred (p=0.05).

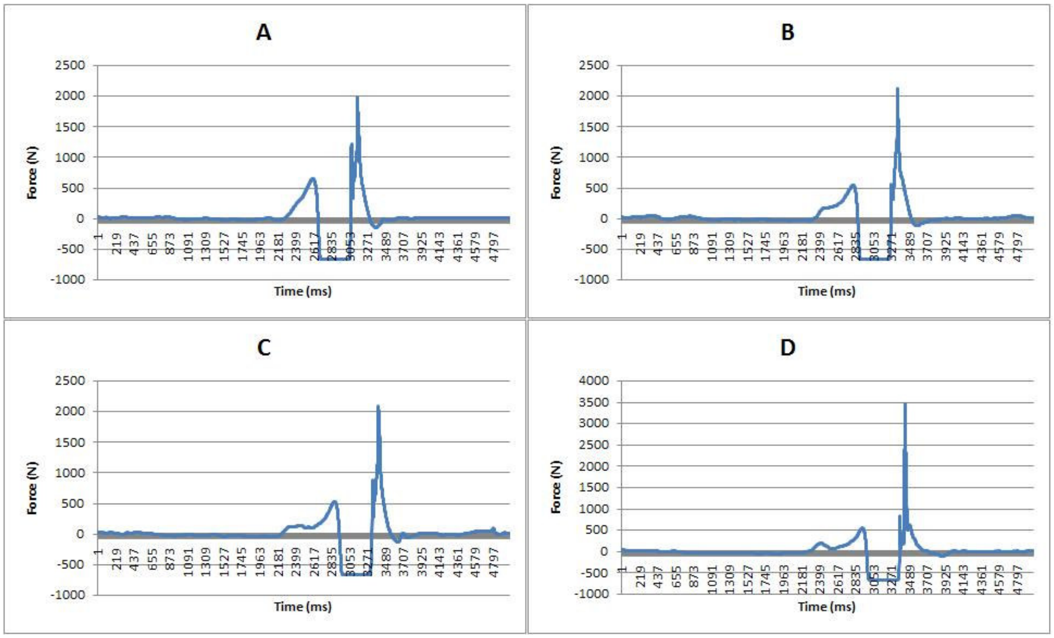


Figure 4: Representative force/time histories for each set tuck index (Subject 12). (A) 73.8% TH; (B) 62.7% TH; (C) 56.6% TH; (D) 49.3% TH.

Impulse Durations

The repeated measures ANOVA revealed significant differences in impulse duration ($F_{(4,108)} = 42.203$; $p = 0.000$). Subsequent pairwise comparison among the conditions revealed that all conditions were different from each other, except for preferred and 62.7%. The least tucked position (73.8% TH) displayed the shortest time segment, and all other conditions were significantly longer compared to this condition. Mean time segments and their standard deviations are presented in Table 4.

Tuck Index (%)	Mean ± SD (ms)
Preferred (64.6)*	443.5 ± 157.5
73.8	346.6 ± 63.5
62.7*	459.2 ± 66.9
56.6*	533.6 ± 106.6
49.3*	589.8 ± 146.8

Table 4: Mean impulse duration data for each condition. * denotes significance (p=0.05) from least tucked position (condition 2).

Center of Mass Excursion

Comparison of center of mass excursion revealed a significant difference ($F_{[4, 108]} = 72.1$; $p = 0.000$) across tuck indexes. Pairwise comparison of the mean values of center of mass excursion revealed that the center of mass had the smallest excursion at the 73.8% Tuck Index with a significant increase as tuck index decreased. There was no difference between preferred and 62.7% Tuck Index. Mean center of mass excursion data are presented in Table 5.

Tuck Index (%)	Mean ± SD (cm)
Preferred (64.6)*	32.3 ± 12.0
73.8	23.9 ± 1.5
62.7*	34.0 ± 2.1
56.6*	39.5 ± 2.5
49.3*	46.2 ± 2.9

Table 5: Mean center of mass excursion data for each condition. * denotes significance (p=0.05) from least tucked position (condition 2).

CHAPTER V

DISCUSSION

Briefly, we found that the impulse generated was the same across all conditions, while the push off impulse duration and center of mass excursion were both smallest at the least tucked position and significantly increased at all other conditions.

Hypothesis 1

The finding of similar impulse values across conditions was contrary to our hypothesis. Although the impulse produced at each condition in the current study was the same, the effect of impulse on swim performance should not be ignored as faster swimmers are reported to produce a higher impulse than slower swimmers (Blanksby et al., 1996a), and that higher impulses are related to faster round trip times (Blanksby et al., 2004). The point here is that these studies examine the effect of the impulse produced *between* swimmers while the present investigation examined the effect of position on the impulse produced *within* a swimmer.

The impulse values collected for these jumps are smaller in magnitude than those previously reported for the freestyle flip turn, but larger than that reported for backstrokers who utilize a similar turning style (Table 6). This difference may be attributed to subject demographics or the fact that the subjects in this study were jumping against gravity whereas the swimmers in the referenced studies were pushing off against drag forces. These results seem to implicate that the drag forces that freestyle swimmers experience during turning are less than the force of gravity (Lyttle et al., 1999). While it would seem that the backstrokers should follow this trend, it is possible that subtleties in the backstroke turn could affect impulse production (i.e. pushing off in supine rather than prone position, needing to rotate to prone position to flip, etc.). Further, the present study did not report peak force values, which have been implicated in the optimization of swim performance (Blanksby et al., 1996a, Blanksby et al., 1996, Blanksby et al., 2004, Lyttle et al., 1999, Cossor et al., 1999). The lack of temporal information included in peak force values, limits the usefulness of this variable in terms of overall swim performance.

Study	Subjects	Impulse (Ns)
Nicol et al., 1979	5 trained university swimmers	217 + 28
Takahashi et al., 1983	6 adult males (3 trained, 3 untrained)	262.7 + 53.8
Blanksby et al., 1996a	36 age group swimmers	177.2 ± 50.2
Lyttle et al., 1997	3 national and international male swimmers	247.3 + 29.02
Lyttle et al., 1999	30 experienced male swimmers	204.0 + 54.9
Blanksby et al., 2004	36 age group backstrokers	55.6 + 12.6
Current Study	28 recreational swimmers	142.3 + 38.6

Table 6: Impulse data from selected studies including current study. All data are presented as mean + SD.

It should also be noted that all but two of the above referenced studies included experienced or trained swimmers in the sample. The current study, for the most part, sampled from recreational swimmers, indicating that there may be some effect of training on impulse generation. The two studies that reported the lowest impulses (Blanksby et al., 1996a, Blanksby et al., 2004) both utilized age group swimmers only, further lending support to the idea that experienced swimmers generate higher impulses claim.

Finally, the lower impulse values could be at least partially related to the lack of ankle range of motion control. It is well known that the torque production capability of the ankle plantarflexors increases as the ankle is brought from plantarflexion into dorsiflexion (Sale et al., 1982; Maganaris, 2003). This means that individuals who jumped with more dorsiflexion could potentially generate more force than those who jumped with more plantarflexion.

Hypothesis 2

The hypothesis of the shortest push off impulse durations at the least tucked position and increased from that position as a more tucked position was assumed was supported. Significant differences between all conditions from the least tucked position (73.8% TH) indicated that as the subject squatted more, it took longer to push-off. The push off phase of the squat jump and wall contact time during a flip turn can be considered as the same phase, because swimmers generally begin pushing off of the wall once foot contact is initiated. This allows us to compare the impulse duration in the present study to previously reported wall contact times.

The time duration (0.46s) at the tuck index of 62.7% (previously reported to be associated with faster swimmers) in the current study is nearly identical to that reported for the actual flip turn (0.47s) (Blanksby et al., 1996a). Further, the time segment at the least tucked position (0.346s) is relatively close to the total wall contact time reported for a sample of experienced swimmers (0.324) (Lyttle et al., 1999). This may suggest that more experienced swimmers use a less tucked position during turning.

Hypothesis 3

As hypothesized, the excursion of the center of mass was significantly more as a more tucked position was assumed.

Previous flip turn research has largely failed to report the excursion of the center of mass during the flip turn, making comparison of the current results to actual flip turn kinematics difficult. One such study reported mean original trochanteric height as 83.4cm and mean tuck index as 0.6, making calculation of center of mass excursion possible (Blanksby et al., 2004). The trochanteric height during the flip turn in these subjects was 50.0cm, meaning that the center of mass excursed 33.4cm. These data are strikingly similar to the current study in which mean center of mass excursion for the tuck index of 56.6%, or 0.566, was 39.5. These results follow the trend of a higher tuck index necessitating less center of mass travel. This indicates that the conditions in the current study do a reasonable job of placing the subjects in a position comparable to the flip turn.

Impact of Dependent Variables on Swim Performance

In terms of swim performance enhancement, it is necessary to account for all variables analyzed. Because the impulse generated at each condition was the same, the performance implications of impulse on the flip turn and swim performance of one swimmer are seemingly negligible. The following recommendations are made under the assumption that the trend of impulse values being no different across different squat depths holds true for an actual flip turn as well as a squat jump. Because success in swimming is measured by time spent performing, minimizing total time or distance covered is critical. The results of the current study suggest that the optimal flip turn would be performed at a tuck index around 73.8%, as it was the position that required the least amount of time to generate the similar impulses across conditions. Wall contact time has been reported to have significant and positive correlations between 50, 5.0, and 2.5m RTT in swimmers (Blanksby et al., 1996a, Blanksby et al., 2004). The turning component of a freestyle swim race comprises 21% of a 50m race, and up to 33% in a 200m race (Chow et al., 1984). It can be seen, then, that minimizing turn time would decrease these percentages and allow for a greater percentage of each race to be spent actually swimming. The result that push off impulse duration in the current study was shortest at the 73.8 TH condition and was significantly longer for the others suggests that a flip turn in this position would result in faster swim times, is in contrast to work that has demonstrated no relationship between wall contact time and 2.5m round trip times (Blanksby et al., 1996b).

Additionally, the tuck index of 73.8% required the least center of mass travel or, in performance terms, it required the swimmer to cover a shorter distance. Center of mass travel relates to the overall amount of distance covered by the swimmer in a given event. The assertion that a, "higher tuck index means that the swimmer travels less distance to and from the wall to reach the designated 50m, 5.0m, and 2.5m marks sooner" (Blanksby et al., 1996a) is supported in the current study by the comparison of center of mass excursion values. For the "faster turns", the center of mass travelled less distance, indicating that for flip turns performed further away from the wall, the swimmer's center of mass will travel less (Blanksby et al., 1996a).

In conclusion, the current study indicates that the impulse was the same across 5 different simulated flip turn positions, but the time spent pushing off and the distance travelled by the center of mass was smaller for a less tucked position. Hence, a flip turn in which the legs are less tucked is seemingly preferred. This recommendation comes in general agreement with previous flip turn research (Cossor et al., 1999, Blanksby et al., 1996a). Clinically, these results suggest that swimmers should be coached into flip turn positions in which the legs are more extended in order to take advantage of the lower times and center of mass excursions.

Limitations

The current study does have several limitations, in addition to the limitation mentioned in the first chapter that hinders the ability to compare the results to real-world swimming performance. First, we do not know if the trend of impulse values being the same across squat depth conditions holds true for the actual flip turn, limiting the comparison of the output variables to actual flip turn performance. Also, the lack of control for ankle range of motion may have affected the individual's ability to produce force differently, perhaps resulting in different impulse values. The lack of strong support for the mechanical similarities between the flip turn and the squat jump limits the usefulness of the performance implications as a result of this study. Finally, we do not know how individuals coordinate the push off for a flip turn. It is possible that a completely different lower extremity muscle activation pattern is used, which would further the limit the use of the squat jump in studying flip turn mechanics.

Recommendations

Direction for future research should include correlations between the tuck indexes during swimmers preferred flip turn strategy and their preferred squat depth during a squat jump. This will strengthen the use of the squat jump as a land-based tool to analyze flip turn mechanics, as well as guide training programs by seeking the positions that swimmers use during swimming for strength training.

Also, better kinematic descriptions of the flip turn in terms of joint angle ranges of motion for the hip, knee, and ankle would be extremely useful and would allow for a more clear understanding of the mechanics involved with flip turning. Further, studies that compare the kinetics of flip turns performed at different tuck indexes within subjects would be extremely useful to further understand the effect of tuck index on flip turn kinetics. Finally, quantification of the eccentric component of the flip turn and the effect of the stretch-shorten cycle on the flip turn mechanics will lend a better understanding as to how the body produces the force necessary to push off of the wall, and could guide strength training programs to optimize this factor.

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