Measuring force-time variation in competitive racing dives

by Wolfgang Nützel and Adolf Thoma

Proper execution of the racing dive in competitive swimming has tramendous bearing on the outcome of short- and medium-length races. In order to more closely examine parameters which influence the starting process, a diving platform equipped with strain gages was developed which measures the time-dependent variation in the horizontal and vertical takeoff forces created by the swimmer. Described are the construction of the measuring system and trials by accomplished swimmers.

The maxim of high-performance athletics "faster, higher, farther" calls for constant refinement and optimization of technique through analytical and experimental training methods. The knowledge of many different sciences, therefore, guide and influence the training techniques used in most sports today. Playing a significant role in this advancement is the field of biomechanics, particularly the branch of "performance biomechanics". Work carried out in this area includes technique analysis and control and requires highly sophisticated measuring methods and instrumentation.

There are, of course, extremely diverse approaches to evaluating athletic performance. Prerequisite to any method chosen, however, is noninterference of the measuring instrumentation with the dynamic execution of the athlete. This means that the measuring system should conform to the specific requirements of the sport under study. In addition, any scientific study must ensure against risk of injury to the athlete.

Difficulties often arise when attempting to fulfill these conditions, most frequently because the standardized design of athletic equipment does not enable the application of ready-made off-the-shelf measuring equipment. This type of problem surfaced in a study intended to analyze racing starts in competitive swimming. In order to reproduce actual conditions occurring in the sport, it was necessary to perform the racing dives from a standard starting block approved for racing competition. According to international rules, starting blocks must have a take-off platform measuring 50 cm (19.6 in.) by 50 cm, sloped 5 deg towards the water's surf ace. The goal of the experiment was to develop a portable take-off platform containing a measuring system capable of detecting those parameters with greatest influence on the racing start (excluding the back-crawl-stroke start).

The start is probably the most decisive moment in swimming races up to and including 200 m (656 ft) in length. A textbook example of the start's physiological and physiological influence on the outcome of a race is clearly illustrated by the 200 m freestyle final during the 1984 Summer Olympic Games (Los Angeles). After an outstanding start, Michael Gross (Federal Republic of Germany), found himself in the lead and throughout the race was able to maintain continuous control over the field.

The proper procedure for a racing start, which covers the time up until transition into the appropriate swimming stroke, is stated in competition rules and is divided into the following phases:

- Preparation for start
- Long whistle: Mounting the back of the starting block
- Command "Take your marks": Assuming a ready but relaxed starting position on the front edge of the starting block
- Sounding of the starting gun
- Leaving the mark
- Flight, entry, glide, initial strokes.

The so-called grab start is the most popular and most effective starting technique in contemporary competitive swimming. As shown in **Fig. 1**, the athlete "grabs" the front side of the starting platform with both hands and pushes off of it during the jump. The older armswing start, whose sequence of movement is illustrated in **Fig. 2**, is by comparison hardly used anymore. This method is still seen in relay racing-because the take-off swimmer can more easily see the touch-off of the oncoming teammate.

The execution of a good racing start is dependent to a very large degree on the power of the jump, assuming a technically flawless follow-through. Another critical determining factor is the duration of the motional sequence beginning with the sounding of the starting gun and ending as the feet leave the block, which includes the swimmer's motor reaction time. Optimization of the latter phases of the start, such as flight, entry, and glide, depend less on the power and speed of the leap than simply on the swimmer's coordinative capability —for example, motor control or feeling for the water.

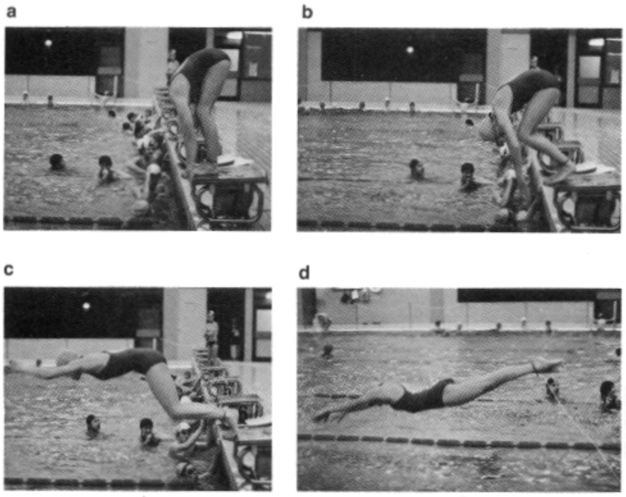

Fig. 1: Grab start is the most popular and effective starting technique. Swimmer "grabs" front of starting block with both hands and pushes off during the jump

Based on these criteria, the development of a measuring system had to take into account the physical parameters illustrated in **Fig. 3**. These parameters include:

- The complex jumping force, defined as the force applied to the take-off platform broken down into vertical and horizontal force components F_v and F_h.
- The complex starting time, defined as the end time t_2 from starting-gun fire until the moment of transition from gliding into swimming. By measuring the interim time t_1 between the starting gun and leaving the starting block, the duration of the jump is determined.

Strain gages or piezoelectric crystals are most typically used as the measuring elements in the various types of biomechanical multicomponent force-measuring platforms built up to this point, although in more recent studies, capacitive transducers have also been applied. For technical and financial reasons, this study was carried out using a platform based on strain-gage force measurement. This method has already been applied in many studies of motional sequences in athletics. The force-measurement platform was built in the workshops of the Technical Center at Bayreuth University, West Germany.

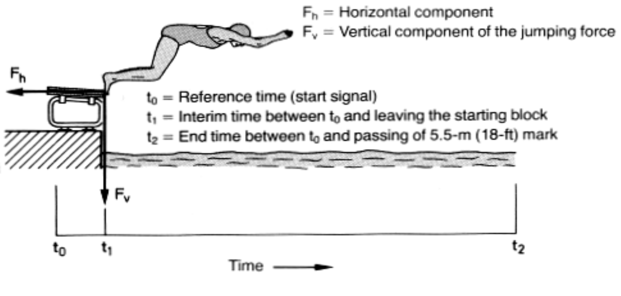

Fig. 3: Measured parameters consist of jumping forces F_v and F_h interim time t_1 until leaving block, and end time t_2 up to transition into swimming stroke

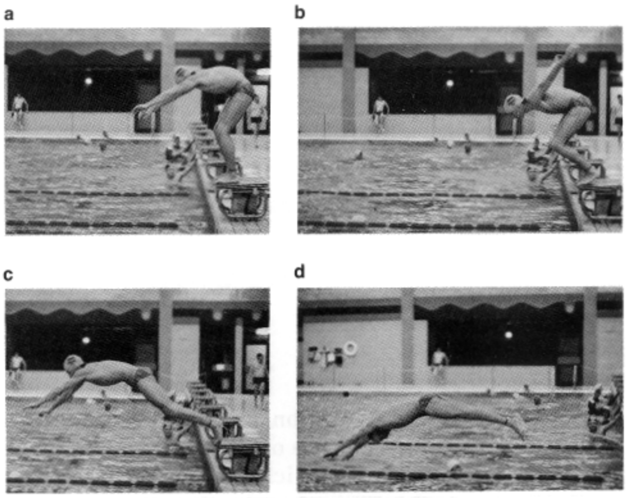

Fig. 2: Arm-swing start has become outdated but is still used in relay racing where the take-off swimmer must be able to see the touch-off of his teammate

In order to prevent the measuring instrumentation from influencing the performance of the swimmers, the force-measurement platform had to be mountable to one of the fixed starting blocks at the test location in the Bayreuth Swim Club. The starting block consists of welded steel-tubing (visible in Figs. 1 and 2) and a detachable take-off platform made of roughened plastic.

Take-off platform as force transducer

The basic construction of the takeoff platform developed for this study is shown in **Fig. 4**. The platform consists of three vertically stacked metal plates:

- **Base plate.** Serves as the mounting plate for connection to starting-block tubing by means of four double-bridge mounting supports.
- **Measuring plate.** Equipped with strain gages, this plate is bolted to the base plate in isolation in order to eliminate the need for side bracing.
- **Top plate.** Covers the measuring plate.

The measuring principle is such that the force exerted by the swimmer during the start is transferred from the top plate to the measuring plate and separated into its horizontal and vertical components for detection. The force-measuring elements are actually short bending beams along the circumference of the measuring plate. onto which strain gages are strategically located. The measuring plate is milled to a specific form such that the bending beams lie between the plate's force-introduction points and force-bearing points. The stresses induced in these beams as the result of forces exerted by the top plate are large enough to be detected and converted to a unidirectional force.

At the force-introduction and force-bearing points between the base plate and measuring plate, as well as the measuring plate and the top plate, are distance washers which create spacing of 10 mm (0.39 in.) and 7 mm (0.28 in.) respectively. The spacing washers aid in creating a fixed force-application point yet allow un restrained deflection of the bending beam in the vertical direction. The plates are bolted together with hexagonal recess bolts.

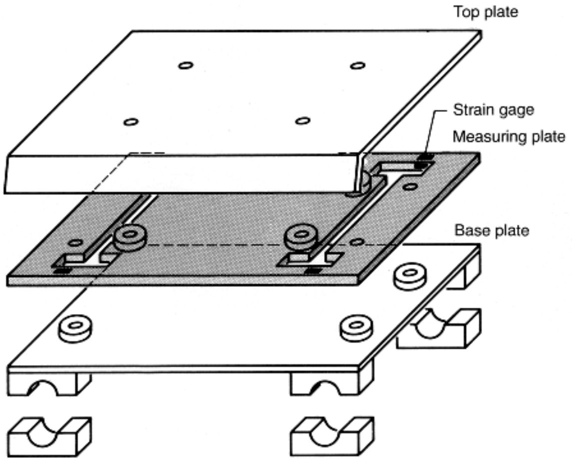

Fig. 4: Measurement platform: Baseplate mounts to starting block, measuring plate is equipped with strain gages, top plate transfers forces to measuring plate

The top plate and base plate are made of 8-mm-thick (0.31-in.) stainless steel and measure 50 cm (19.6 in.) by 50 cm. The material Dural was chosen for the 12-mm-thick (0.47-in.) measuring plate because its relatively low modulus of elasticity (E ≈ 70,000 N/mm^2, 1462 lb/ ft^2) makes it especially suitable for the transformation of the applied force to measurable strain.

Methods of force and time measurement

Sizing of the cross section and length of the bending beams was determined on the basis of estimated diving forces. First trials showed, however, that the initial estimations were too high: Maximum force values actually lay at about 1100 N (247 lb) in the horizontal direction and 1500 N (337 lb) in the vertical direction. Design was based on the known deflection characteristics of a bilaterally fixed bending beam and led to dimensions illustrated in **Fig. 5.** Chosen as measuring elements were metal-foil strain gages with a nominal resistance of 350 ohms (HBM Type 6/350 LY 63). A fast-setting adhesive (HBM Type Z70) was used to mount the strain gages.

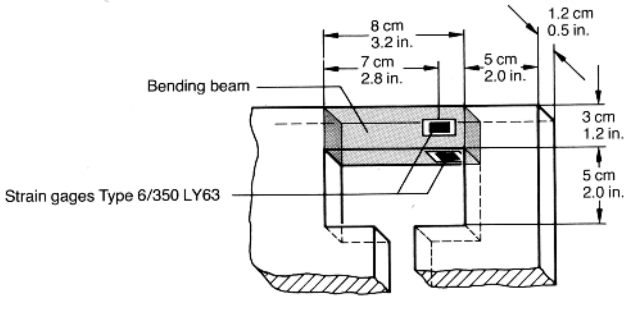

Fig. 5: Design was based on the known deflection characteristics of the bilaterally fixed bending beam and lead to dimensions illustrated above

Vertical-force components are detected by applying strain gages to the upper and lower side of each bending beam; horizontal components are detected by straingage placement on the inside surface of each beam. Strain gages were located at the ends of the bending beam to take advantage of the larger stresses which occur there.

The eight strain gages used to measure the verticalforce component are arranged in a Wheatstone fullbridge configuration. Each bridge arm is composed of two strain gages connected in parallel. A circuit diagram for this configuration is shown in **Fig. 6**, whereby U_A corresponds to the measuring voltage and U_B corresponds -to the bridge excitation voltage. The remaining four strain gages are also connected in a full bridge to measure the horizontal component, as shown in **Fig. 7**.

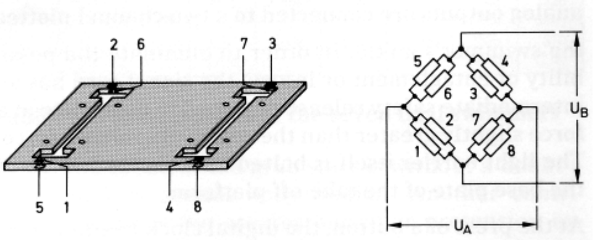

Fig. 6: Eight strain gages used to measure the vertical force component are arranged in a Wheatstone fullbridge configuration. Each bridge arm is composed of two strain gages connected in parallel

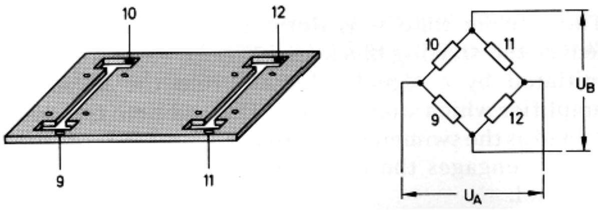

Fig. 7: Horizontal force component is measured by four strain gages, also connected in a full-bridge circuit

Measuring signals from both circuits are processed by two 5-kHz carrier-frequency measuring amplifiers (HBM Type KWS 82.D7). The analog outputs of this measuring amplifier were connected to a two-channel plotter supplemented with a time-recording channel so that the time-dependent behavior of horizontal and vertical forces could be plotted. **Fig. 8** shows these instruments. Before the take-off platform was mounted ' to the starting block, it was calibrated using known weights.

The following materials were used to track time during the racing start: Commercial-size digital clock with interim-period display (resolution 0.01s), an electrical starting buzzer, light barrier, and signal cable. A signalcord length of 5.5 m (18 ft) was arrived at using empirical values from earlier studies [3]. One end of the signal cord is knotted to a cotter pin, which is linked loosely by ball clamps within the channel of the light barrier. The other end is secured with a nylon strap to

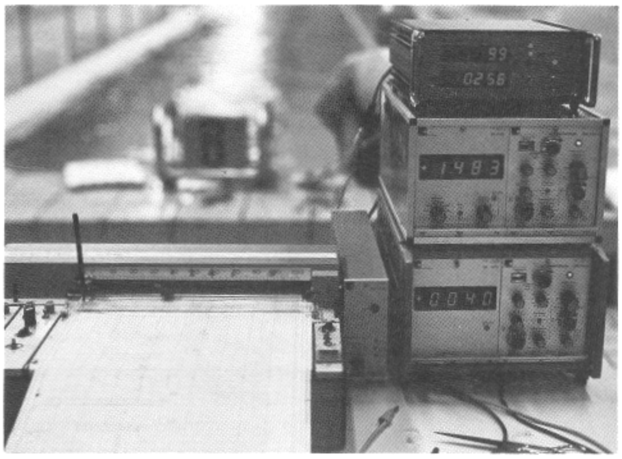

Fig. 8: Measuring signals are processed by two 5-kHz carrier-frequency measuring amplifiers. Amplifiers' analog outputs are connected to a two-channel plotter

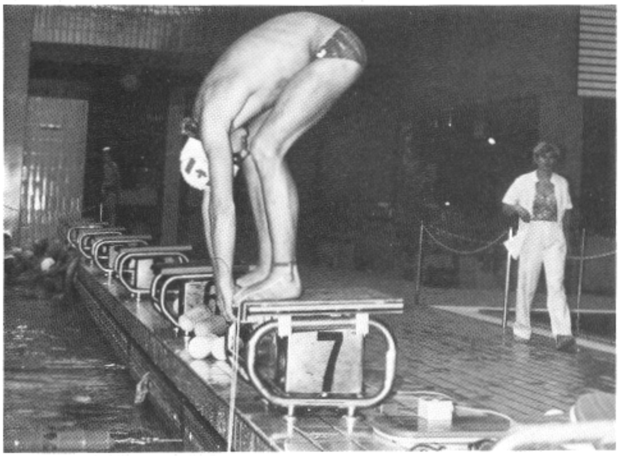

Fig. 9: Grab start stance is taken by the swimmer and signal cord lies out of harm's way shortly after the command "take your marks" and before the start

the swimmer's ankle. In order to eliminate the possibility of entaglement or injury, the signal cord has an intermediate safety release designed to disengage at a force slightly greater than the cotter-pin release force. The light barrier itself is bolted onto the underside of the base plate of the take-off platform.

At the press of a button, the digital clock begins counting and the starting buzzer sounds. To prevent interruption of the data-recording process, the starting button is then electronically blocked for the duration of the trial. A single-pole switch causes the buzzer as well as the plotter to receive a short pulse such that the buzzer gives a short audible signal and the plotter records a short vertical marking.

The interim time t_1 is determined as the swimmer leaves the starting block (see Fig. 3). Measurement is initiated by a signal released from the measuring amplifier which stops a clock. The end time t_2 is determined as the swimmer reaches the 5.5-m (184 t) position and disengages the cotter pin from the light-barrier channel.

Racing-start trials and results

After various preliminary trials, the entire measuring system was tested under actual conditions. Swimmers included three female athletes and four male athletes from the Bayreuth Swim Team.

The first two phases of the starting process-long whistle and mounting the starting block-were eliminated on the possibility that the signal cord could tangle in the starting block. Only after mounting the starting block was the signal cord attached around the swimmer's ankle. **Fig. 9** shows the stance taken by the swimmer and position of the signal cord after the command "take your marks" and shortly before the start. After the starting button is pressed, a buzzer sounds, the time-measurement system switches on, and the plotter begins recording.

The seven trial swimmers completed a total of 37 starts. In order to enable establishment of intra-individual differences, five swimmers performed both the grab start and the arm-swing start. The remaining two performed only the grab start. The technical execution of each dive was judged by experts as either very good, good, average, or poor. Several starts were also filmed. A generally valid statement about the starting process is not possible at this time because of the low number of trial starts carried out, however existing data do allow some isolated conclusions.

Fig. 10 shows the typical force-time curve for the grab start. The upper curve indicates the time-dependent vertical force, whose plot can be broken up into five phases beginning at point A:

Phase 1: Mounting the starting block. The measured force F_V increases from zero to a force corresponding to the swimmer's body weight.

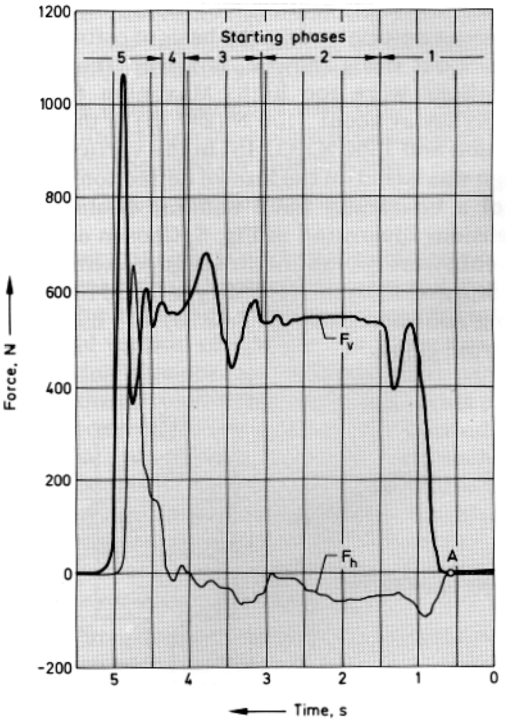

Fig. 10: Typical force-time curve for the grab start can be broken up into five phases beginning at point A

Phase 2: The swimmer stands with both legs straight on the starting block.

Phase 3: On the command "Take your marks", the swimmer assumes the grab-start position. The act of bending the upper body and the knees initially creates a load reduction. The following deceleration of this downward momentum causes a load greater than body weight. This unloading and loading was to a small or large degree clearly distinguishable in the verticalforce component of every swimmer. Striking is the fact that maximum load is many times larger than the unloading. According to reference [2], this phenomenon can be explained by the fact that a movement can be brought to a stop faster than it can be begun.

Phase 4: While the swimmer is in the grab-start position, the vertical-force component lies slightly above the body weight of the swimmer, althought no additional force can realistically be expected. In this case, the additional force amounts to about 10 N (2.2 lb). This increase was observeable in all of the starts.

Phase 5: The take-off segment indicates the actual force pattern during the racing start. This is typically characterized by a small load increase followed by a distinct load release, created by the swimmer's act of falling forward as the knees are bent. The release of the hands from the grab position cannot be discerned in the vertical-force component. The maximum vertical force is reached when jumping and amounts in this start to 1060 N (238 lb).

The horizontal force component represented in the lower curve of Fig. 10 is basically inconsequential up until phase 5. The negative deflection exhibited before this point is caused by a 5 % slope in the take-off platform. Only in phase 5 does the curve show a positive, almost vertical deflection. Note the short offset in the curve at a horizontal force of about 160 N (36 lb). This is caused by the release of the horizontal pressure induced by the hands on the front edge of the take-off platform. The rest of the force pattern is uniform and reaches a maximum value of about 660 N (148 lb).

The force-time curves of the arm-swing start are almost identical to the grab start up until phase 5 when the different motional sequences become clearly identifiable. Interesting is that in almost every case, the maximum-force values are greater for the arm-swing start than for the grab start.

It is also interesting to note that the vertical-force component of a jump is almost always greater than the horizontal-force component. In a few cases, the components were equal. Nevertheless, all of the swimmers exhibited strongly individual characteristics. Note, however, that differences in maximum force between members of the opposite sex having the same body weight are indiscernible.

The **Table** lists the best starts recorded by each swimmer. Evident is that the grab start is faster than the arm-swing start at both the interim time and the end time. This confirms the results of earlier studies [3, 4]. The speed of the grab start is without a doubt a result of less overall body motion. Another contributing factor is the greater muscular pretension exhibited in the grab start.

Swimmer No.	Sex	Weight, kg (lbs)	Starting technique	Judge's comment	Interim time t_1, s	Final time t_2, s	F_v max, N (lbs)	F_h max, N (lbs)
1	m	63 (139)	grab	good	0.80	2.56	830 (187)	820 (184)
			arm-swing	average	1.03	2.85	830 (187)	840 (189)
2	m	72 (159)	grab	v. good	0.83	2.43	1080 (243)	830 (187)
			arm-swing	average	1.00	2.61	1090 (245)	1000 (225)
3	m	75 (165)	grab	v. good	0.71	2.51	1125 (253)	970 (218)
			arm-swing	good	0.99	2.56	1230 (277)	1030 (232)
4	f	52 (115)	grab	v. good	0.89	2.57	800 (180)	560 (126)
			arm-swing	v. good	0.70	2.78	780 (175)	660 (148)
5	f	59 (130)	grab	v. good	0.91	2.64	735 (162)	680 (153)
6	f	56 (123)	grab	v. good	0.81	2.78	800 (180)	620 (139)
7	m	72 (159)	grab	v. good	0.81	2.15	1200 (270)	920 (207)
			arm-swing	good	0.91	2.36	1300 (292)	970 (218)

Table: The fastest starts of the seven trial swimmers

Other conclusions remain open to speculation. One puzzling result is that a fast interim time does not necessarily result in a fast end time. This applies to comparisions made between different dives of the same swimmer as well as to comparisons between different swimmers. Also, the assumption that the fastest end time in each case is related to the maximum values of the vertical and horizontal force components was not confirmed by the measured values.

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