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The Effects of Plyometric Warm-up on Lower Limb Muscle Activity and Time to 10m in the Backstroke Swimming Start

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Abstract The backstroke swim start is an explosive, discrete skill. Swimmers often perform plyometric warm-up protocols, such as repeated jumps, prior to their race. The purpose of this study was to determine the impact of repeated drop jumps performed immediately prior to a backstroke start. Nine elite backstroke swimmers performed three starts after a standard swimming warm-up, and three after an additional plyometric warm-up (three drop jumps from a height of 0.4 m) prior to each start. Timing and peak activation of gluteus maximus and vastus lateralis activity were measured using wireless surface electromyography. Hip and knee angles, wall contact time, head entry distance and time to 10 m were recorded using digital video cameras positioned at the side of the pool. On average, starts performed after the plyometric warm-up had a 0.1±0.09 s longer time to 10 m, peak gluteus maximus activity occurred 0.09±0.13 s later and peak vastus lateralis activity occurred 0.15±0.16 s earlier. Head entry distance was inversely proportional to time to 10 m (r = -0.80) across both conditions and should be considered as a training target. Performing plyometric warm-ups immediately prior to races may have a negative impact on backstroke start time to 10 m.

Keywords Biomechanics, Swim Start, EMG, Training

1. Introduction

The swim start is an important contributor to race performance, especially in sprint events where races are won by as little as 0.01 s [1]. The Federation Internationale de Natation (FINA), the world regulatory body for competitive swimming, has approved various modifications to backstroke start rules and equipment over time. These improvements include the introduction of the backstroke ledge (also referred to as the “backstroke wedge” or “backstroke start device”; Omega OBL2, Swiss Timing, Coregmont, Switzerland) in 2014. The backstroke ledge has resulted in faster start times [2-5]; however, coaches and athletes continue to search for competitive advantages.

Several parameters can be targeted to improve backstroke start performance. As discussed in a review of swim start research [6], improving reaction time may result in a lower start time. Also, larger impulses directly result in greater takeoff velocities per the impulse-momentum relationship. Swimmers can increase impulse by applying a greater average force or by increasing block contact time (time spent in contact with the starting surface). Furthermore, applying the same impulse over a shorter time (thus applying a greater average force) would also represent an advantage, since takeoff velocity would be the same while block contact time would be lower. In dive starts, increasing block contact time by shifting weighting to the rear of the block results in greater takeoff velocities, but also a greater time to five meters [7]. Accordingly, the primary focus for increasing impulse should be applying larger forces to the wall. Specific modifications to warm-up protocol may increase horizontal force through post-activation potentiation (PAP).

PAP is an increase in contractile force after a conditioning contraction, which is typically close to the participant’s maximum voluntary contraction [8]. It is unclear whether PAP can improve athletic performance [9]; however, some evidence suggests it may play a role in the backstroke start. For example, performing a three repetition max (3RM) squat results in greater peak horizontal and vertical forces during a subsequent swimming dive start [10], although it did not significantly affect the time to 10 m. Additionally, individuals can achieve greater countermovement jump heights after performing a 5RM squat [11]. However, these exercises are impractical in a competition setting. In contrast, a plyometric warm-up is more practical, and may provide a similar form of conditioning contraction. Plyometric training protocols throughout a swimming season can increase swim start performance [12, 13]; however, the impact of including plyometric exercises in a swimming warm-up is unclear. Performing drop jumps prior to countermovement and squat jump exercises results in greater subsequent jump height [14], which may be explained by PAP. Since time to 10 m and maximum jump height are inversely correlated in the swimming dive start [15], a warm-up which increases maximum jump height may result in a faster time to 10 m in the backstroke start as well. To our knowledge, however, this has not yet been examined.

Timing of hip and knee joint extension has also been analyzed in backstroke starts. Some evidence indicates that faster backstroke starts are characterized by an earlier and greater magnitude of hip extension relative to knee extension [16]. Similarly, a proximal to distal order of joint extension also results in greater squat jump performance in both live participants and computer models [17, 18]. However, this proximal to distal order of joint extension has not been consistently observed in backstroke starts [2]. This may indicate that some swimmers have difficulty achieving a proximal to distal order of muscle activation.

The purpose of this study was to evaluate the effects of plyometric warm-up (0.4 m drop jumps) on backstroke start performance by examining muscle activation and kinematics. It was hypothesized that starts performed after a plyometric warm-up would display a lower time to 10 m, greater head entry distance, greater amplitude and earlier onset of gluteus maximus activity, lower wall contact time, earlier activation of the gluteus maximus relative to vastus lateralis, and earlier extension of the hips relative to the knees. We also hypothesized that there would be an inverse relationship between the head entry distance and time to 10 m, supporting previous findings [4].

2. Materials and Methods

2.1. Participants

This study was approved by the University of Western Ontario’s Health Sciences Research Ethics Board and all participants provided written informed consent. Nine swimmers (2 males and 7 females, 19.3 ± 1.4 years old, 671.4 ± 35.7 FINA points in a backstroke event) that were competing at the Canadian National level or higher participated in this study. All swimmers were regularly training, including training on backstroke starts, for the six-month Varsity season immediately prior to data collection. Participants were injury free at the time of data collection and their personal best time in a backstroke event scored a minimum of 600 FINA points per the 2016 FINA ranking table. FINA points are calculated based on the swimmer’s time relative to the latest world record, where a time equal to the world record would score 1000 points [19]. The 600 FINA point criteria reflected that the swimmers were competitive at the Canadian National level or higher.

2.2. Procedure

All testing was performed in an indoor 50 m pool heated to 28°C. All participants performed a standard warm-up, which included 900 m of mixed swimming and drills as well as two practice starts. This warm-up is comparable to one that these swimmers would typically complete prior to a competition. After warm-up, participants were instrumented with wireless surface electromyogram sensors and completed maximum voluntary isometric contractions (described later). Next, participants performed six 15 m maximal-effort starts from which data were collected for this study. Three starts were performed without any additional warm-up, and three starts after a plyometric warm-up (swimmers performed three drop jumps from a height of 0.4 m immediately prior to each start). This height was selected because drop jumps performed from this height result in the greatest takeoff velocities compared to jumps from a height of 0.2 or 0.6 m [20]. Three starts of one type were performed consecutively before switching to the second type. The order that the participants performed the blocks of starts was randomized. At least two minutes of rest were given after each start, which has been routinely used and found to be an adequate recovery period for backstroke starts [2, 4, 21-23].

2.3. Instrumentation

Two wireless surface electromyogram (sEMG) sensors (Trigno, Delsys, Boston, MA, USA) were fixed to the skin of each participant using the manufacturer’s double-sided adhesive skin interface (SC-F03, Delsys, Boston, MA, USA). One sensor was located over the gluteus maximus muscle, and one over the vastus lateralis muscle on the right side of the body. These muscles were selected as they represent major hip and knee extensors. Sensors locations were determined based on recommendations from the SENIAM project [24]. The skin was cleaned with rubbing alcohol prior to placing the sensors to reduce skin impedance. Sensors were placed with electrodes aligned parallel to the muscle fiber direction. Sensors were waterproofed by covering them with an adhesive film (Tegaderm™, 3M™, St. Paul, MN, USA; Figure 1). Voltage signals were sampled at 1000 Hz using a 16-bit analogue-to-digital conversion board (USB-6225, National Instruments, Austin, TX, USA). To simulate race conditions, the pool wall was faced with a FINA-compliant touchpad (Omega OCP5, Swiss Timing, Coregmont, Switzerland), a competition start block was used (Omega OSB11, Swiss Timing, Coregmont, Switzerland) and a backstroke ledge was installed (Omega OBL2, Swiss Timing, Coregmont, Switzerland). The ledge was adjusted to the appropriate position based on each swimmer's preference (i.e. the setting they use in competition). An electronic starter (Daktronics, Inc., Brookings, SD, USA) provided an audible start signal for swimmers and a flash from the built-in strobe. The starter also simultaneously provided an analog start signal which was synchronously captured with the EMG signals.

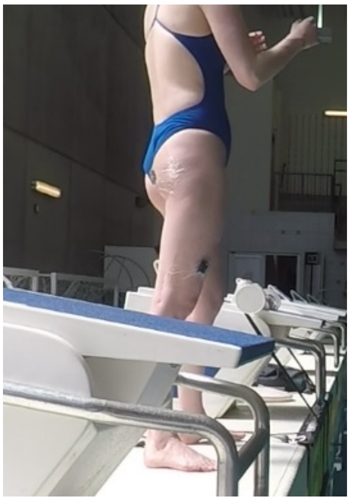

Figure 1. EMG sensors placed on gluteus maximus and vastus lateralis, and waterproofed using 3M^{TM} Tegaderm^{TM}.

All starts were recorded from the side by two high definition digital video cameras (Hero 5 Black, GoPro, San Mateo, CA, USA) with a resolution of 1080p. Video was captured as progressive scan rather than interlaced fields, and accordingly, full images were captured at a rate of 60 Hz. Cameras were set to record in "linear" mode. One camera was located above the water, one meter from the end wall, and was used to track the hip and knee angles throughout wall contact, head entry distance as well as wall contact time. The second camera was located underwater 10 m from the start wall and was used to capture time to 10 m. The two cameras were started synchronously via WiFi using a remote (Smart Remote, Go Pro, San Mateo, CA, USA). The WiFi signal was transmitted from the remote to the underwater camera using an RG-174 coaxial cable (GoPro Underwater WiFi-View, Eye of Mine action cameras, Long Beach, CA, USA). The videos were recorded direct to SD cards in each of the cameras. A 15 m length of fiber optic cable (Simplex 1000UM, Industrial Fiberoptics, Tempe, AZ, USA) transmitted the electronic starter's strobe light to the underwater camera to verify synchronization of the video files. To make digitizing joint coordinates more consistent, several anatomical landmarks were highlighted with a grease marker (Eye Black, Easton Baseball/Softball Inc., Van Nuys, CA, USA); the ankle (lateral malleolus), knee (lateral epicondyle of the femur), hip (greater trochanter of the femur), and iliac crest were marked on the participant's left side. The experimental setup is pictured in Figure 2.

2.4. Maximum Voluntary Isometric Contractions

After their warm-up, participants performed three, four-second maximum voluntary isometric contractions (MVICs) for each muscle separated by a two minute break as recommended in previous literature [25]. For vastus lateralis, participants were seated in a chair with their knee and hip flexed to 90 degrees and they attempted to extend their right knee which was restrained by an ankle cuff and a fixed chain [25]. For gluteus maximus, participants were standing and attempted to extend their right hip which was restrained using an ankle cuff and a fixed chain. Participants held a vertical pole for stability during the glute MVIC. Participants were asked to exert maximum effort during the MVICs and were given verbal encouragement. Participants viewed a computer screen that provided feedback of muscle activity to encourage maximal effort and also indicated when participants should start and stop their contractions. MVICs were confirmed using a maximum-effort vertical jump where participants were instructed to jump as high as possible. If the maximum activity observed during the jumps exceeded the peak activity during the MVICs, then the MVICs were repeated.

Figure 2. The experimental setup used for this study illustrated using single video frames from both video cameras captured at the instant of the start signal. Left image (above water camera view): A) Omega OSB11 with Omega OBL2 attached. B) Light bloom on strobe from electronic starter. C) Grease marker on the ankle for identifying joint location. Right image (underwater camera view): D) Underwater 10 m mark. The white plastic fixture holding the end of the fiber optic cable is apparent around the bright feature (E) of the light flash transmitted from electronic starter strobe.

2.5. Data Analysis

Landmark positions in the video files were manually digitized using Kinovea software (Version 0.8.25). All files were digitized by the same researcher. The upper surface of the starting platform was used as a reference length (0.74 m) to calibrate the video. The front edge of the starting platform, which was even with the touchpad, was used as the origin. Joint angles were calculated using cosine law. The hip angle was calculated from the position of the greater trochanter, lateral epicondyle of the femur and the iliac crest. The knee angle was calculated from the position of the lateral malleolus, greater trochanter and the lateral epicondyle of the femur. Head entry distance was defined as the horizontal distance between the pool wall and the center of the head as it entered the water. Time to 10 m was defined as the elapsed time between the flash from the electronic starter and the instant that the center of the head reached 10 m underwater. The center of the head was used to measure head entry distance and time to 10 m because it is used at competitions to determine a start infraction [remaining underwater further than 15 m; 26]. Wall contact time was defined as the time between the starter flash and the last frame that the swimmer's feet were in contact with the wall [5]. Hip and knee angles were calculated between the instant of the start signal (indicated by a flash from the electronic starter) and the last wall contact. Joint angle data were processed using a 4th order zero-lag 4 Hz low-pass Butterworth filter to reduce noise from manual digitizing error. Residual analysis indicated that this cutoff frequency was optimal [27]. Prior to filtering, padding data was added to the beginning and end of each data record using the reflection technique [28].

sEMG voltages were processed using a custom LabVIEW program (Version 2010, National Instruments, Austin, TX, USA). Signals were processed using a 2nd order 0.1 Hz high-pass Butterworth filter to eliminate baseline drift, full-wave rectified, and a 2nd order low-pass Butterworth filter with a cutoff frequency of 3 Hz was applied to create linear envelope EMG. The time delay created by the single-pass 2nd order Butterworth filter reflects the muscle's electromechanical delay so that the linear envelope EMG resembles muscle force [29]. Amplitudes were then expressed as %MVIC by dividing each trial by the peak voltage from the participant's MVIC trial. Peak EMG activity, time from the start signal until peak EMG activity, and the difference in time to peak between gluteus maximus and vastus lateralis, were then extracted from the resulting linear envelope data.

Statistical analyses were performed using SPSS software (Version 24, IBM, Armonk, NY, USA). A Shapiro-Wilk test of normality was run to determine if parametric statistics were appropriate. Paired, two-tailed t-tests were then performed with thresholds (α) of 0.05. Effect sizes were also calculated using Cohen's d_z, the recommended method of calculating effect size for repeated measures experiments [30]. Cohen's d_z is the mean change score for each participant, divided by the standard deviation of this mean. Thresholds of 0.5 and 0.8 were considered medium and large effect sizes, respectively. Similar to previous research [4, 31], a Pearson's Product-moment correlation between the time to 10 m and head entry distance was performed. Based on guidelines from the literature, correlation magnitudes of 0.6-0.8 were described as "moderately strong", and those 0.8 and above were described as "very strong" [32].

3. Results

Respective means and standard deviations of kinematic and EMG variables are presented in Table 1. All variables were normally distributed ($W>0.05$), with the exception of head entry distance ($W=0.02$) and the difference between time to peak vastus lateralis and gluteus maximus activity ($W<0.01$). However, we proceeded with parametric statistics since all other variables were normally distributed and non-normality does not affect the Type-I error rate in paired t-tests [33]. Performing drop jumps prior to backstroke starts resulted in a significantly higher time to 10 m with a large effect size. Peak EMG amplitude showed a large inter-participant standard deviation, no statistically significant different between test conditions, and small effect sizes. Participants displayed significantly lower time to peak vastus lateralis activity, with a large effect size, following the plyometric warm-up. Time to peak gluteus maximus activity occurred after that of vastus lateralis following the plyometric warm-up, also with a large effect size. The t-tests indicated that the time to peak gluteus maximus activity was not significantly different between test conditions. However, a medium effect size indicated that the peak activation occurred later following the plyometric warm-up. There was a strong negative correlation between head entry distance and time to 10 m ($r = -0.80$; Figure 3).

Table 1. Means and respective standard deviations for starts performed with no additional warm-up (control) or immediately after three drop jumps (plyometric warm-up). *indicates a statistically significant difference at p<0.05. † indicates a large effect size and ‡ indicates a medium effect size.

	Control	Plyometric Warm-up	Effect Size (d_z)	p
Time to 10 m (s)	5.16 ± 0.51	5.26 ± 0.55	1.15†	0.01*
Head entry distance (m)	1.99 ± 0.33	2.00 ± 0.31	0.14	0.70
Wall contact time (s)	0.61 ± 0.04	0.61 ± 0.06	-0.18	0.62
Peak vastus lateralis activity (%MVIC)	146.31 ± 48.58	147.02 ± 54.85	0.02	0.48
Peak gluteus maximus activity (%MVIC)	104.56 ± 55.90	91.76 ± 41.01	-0.47	0.22
Time to peak vastus (s)	0.68 ± 0.16	0.53 ± 0.12	-0.87†	0.04*
Time to peak glute (s)	0.55 ± 0.16	0.64 ± 0.17	0.71‡	0.08
Time to peak vastus vs. glute (s)	0.13 ± 0.26	-0.11 ± 0.16	-0.95†	0.03*
Knee extension onset (s)	0.12 ± 0.06	0.15 ± 0.04	-0.05	0.21
Knee extension average velocity (°/s)	191.39 ± 23.38	178.84 ± 46.47	-0.39	0.27
Hip extension onset (s)	0.07 ± 0.04	0.08 ± 0.06	0.12	0.73
Hip extension average velocity (°/s)	156.33 ± 47.36	164.98 ± 61.73	0.31	0.34
Hip relative to knee extension onset (s)	0.05 ± 0.05	0.07 ± 0.06	0.27	0.44

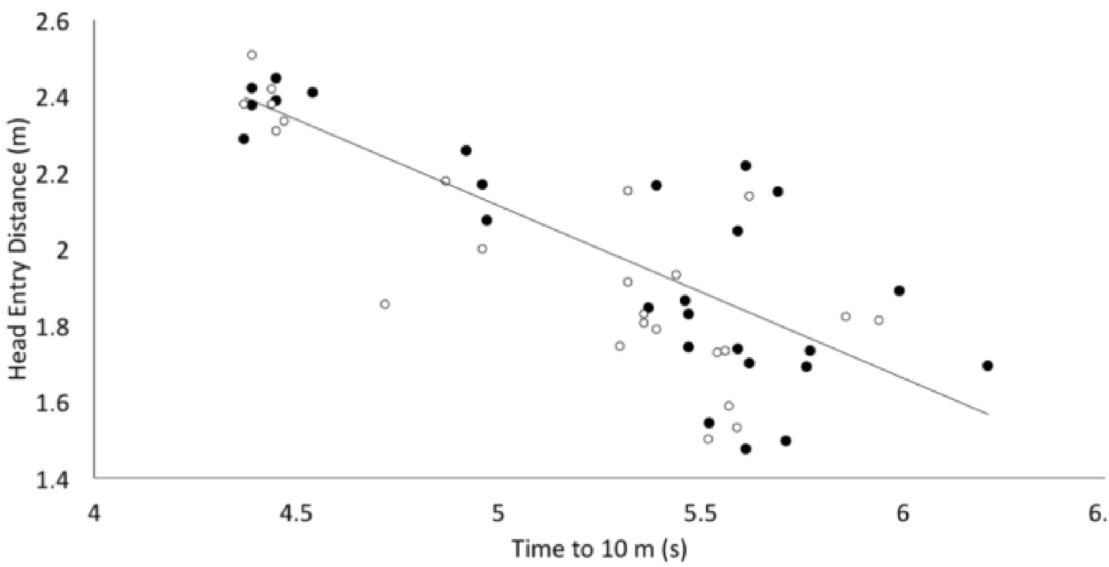

Figure 3. Relationship between head entry distance (m) and time to 10 m (s) for all participants in control (open circles) and plyometric warm-up (filled circles) conditions (r = 0.80).

4. Discussion

The purpose of this study was to quantify the effects of a plyometric warm-up on backstroke start performance. Previous research has used large stimulus contractions, such as a barbell squat, to investigate PAP in swim starts [10] and jumps [11]. This study, however, aimed to investigate an exercise which is commonly used and is practical for swimmers in a competition setting. Results did not fully support the first hypothesis. We observed that starts performed after the completion of a plyometric warm-up had a greater time to 10 m, demonstrating that this warm-up had a negative impact on start performance. Additionally, we observed that starts performed after the plyometric warm-up had significantly earlier peak activation of vastus lateralis and later peak activation of gluteus maximus. This is not consistent with a proximal-to-distal order of joint extension. It remains unclear whether proximal-to-distal joint sequencing is optimal for backstroke starts, as some studies have found it to be associated with a shorter start time [3, 16], while others have not [2, 4]. However, in support of our second hypothesis, we observed that longer head entry distances were strongly correlated with shorter times to 10 m.

Different methods have been used to analyze muscle activation in backstroke starts, making direct comparisons difficult [34]. Both integrated [22] and average [35] EMG have been described during backstroke starts. However, both of these approaches have limitations and should be interpreted cautiously. Integrated EMG is increased by wall-contact time as well as EMG amplitude. Similarly, average EMG also depends on the contact time. Since increased wall contact time has a negative impact on backstroke starts [5], the integrated and average EMG data can be misleading. Furthermore, some research has identified that it is important to understand muscle activation sequence [34], although few studies have examined these data in backstroke starts [35]. To address the importance of muscle activation magnitude and timing, without the confounding factor of wall contact time, we chose to examine peak activation and time to peak activation. Our findings demonstrate the importance of activation sequence. Vastus lateralis and gluteus maximus are nearly maximally activated in backstroke starts; therefore, it may be possible to increase performance through changing activation sequence but not through increased activation.

We observed differences in timing of hip and knee extensor activity between conditions. A proximal-to-distal recruitment of muscle activation and resulting order of joint extension benefits jumps [17, 18] and backstroke starts [16]; however, it should be noted that this is not consistently observed [2, 4]. In this study, peak gluteus maximus activity occurred before that of vastus lateralis in the control condition, but after the vastus lateralis in the plyometric warm-up condition based on a statistically significant p-value and a large effect size. This suggests that the plyometric warm-up may hinder swimmers' ability to extend their lower limb joints in a proximal-to-distal order. However, these differences in timing of muscle activation were not reflected in the onset or rate of hip and knee extension in this study, which were not different between test conditions with statistically insignificant p-values and small effect sizes.

Prior muscle activation creates both muscular fatigue and PAP, which are often difficult to differentiate [36]. We observed a lower time to peak force in vastus lateralis after the plyometric warm-up, which is consistent with PAP. However, since start performance was decreased, and there was a greater time to peak force in gluteus maximus following drop jumps in this study, it appears that the impact of fatigue was greater than that of PAP.

We observed a strong negative correlation between head entry distance and time to 10 m, which is consistent with previous findings comparing starts with and without the backstroke ledge [4]. The relationship between flight distance and start time has also been proposed as an explanation of the shorter race times observed when swimmers use the backstroke ledge [5]. Head entry distance remains a promising coaching target for backstroke starts, as it explains 63% of the variance in time to 10 m in this study, and 58% in our previous study [4]. This indicates that the relationship may hold across different situations, such as when using different types of start blocks, and be applicable to swimmers who use different start techniques. Since head entry distance can be quickly extracted from digital video in a training setting, it may prove useful to determine the start technique that is optimal for individual swimmers.

4.1. Limitations

This study has some limitations, and results should be interpreted accordingly. First, we only studied activation of the hip and knee extensors. Vastus lateralis was selected to represent the action of the quadriceps as it is a monoarticular, superficial muscle and was in a protected location. Gluteus maximus was selected to represent the entire group of hip extensor muscles since it is the largest of the hip extensors. Second, we were unable to capture onsets of gluteus maximus muscle activity for some participants. The glutes maximus was submerged prior to the start signal in four of nine participants, blocking the wireless signal. However, since the gluteal muscles are above the water during a backstroke start, we successfully captured peak and time to peak activity for gluteus maximus in all participants. Third, we chose to examine the wall-contact phase of the start in this study because previous research suggests the plyometric warm-up only affects the explosive "push-off" portion of the start [8, 9]. However, we acknowledge that body position during flight and water entry also affects performance [16, 21, 37]. Fourth, we collected EMG only on the right side, and tracked joint position only on the left side of participants. These data were collected from opposite sides so that the sensors would not be confused with the joint markings. This is appropriate since limb movement in backstroke starts is symmetrical, although we acknowledge that there are likely subtle differences between the left and right sides that are not accounted for in this study. Finally, we did not collect foot and hand forces. Previous research evaluating swimming dive starts [10], relay takeovers [38] and backstroke starts [4, 21, 37] have shown that changes in start kinetics are often not connected to changes in start time. Accordingly, time to 10 m appears to be more sensitive than kinetics as a measure of swim start performance based on the larger effect size.

5. Conclusions

Performing drop jumps immediately prior to a backstroke starts results in a longer time to 10 m. This puts swimmers at a disadvantage in competition. This longer time to 10 m may occur because swimmers do not perform a proximal-to-distal activation of the lower-limb musculature after performing drop jumps; it may also be due to fatigue offsetting the effects of PAP. Further research is needed to examine the impact of different warm-up protocols. Coaches and athletes should continue to capture head entry distance as an objective indicator of backstroke start performance when assessing different start techniques.

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