EFFECTS OF FREEDIVING FIN PARAMETERS ON ANKLE STRESS USING 3DIVE (FREE DIVING VALGUS EXPERIMENT) RIG

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The aim was to investigate the impact of freediving fin parameter on the diver for two different foot morphologies, one without deformation and other with a hallux valgus. It proposes to identify the parameters that have the greatest influence on the stresses applied to the ankle. A complete experimental design with 4 factors was set up. The factors studied were the length of the fin, the stiffness, the water channelling system and the angle between the blade and the liner. A prosthetic foot was used to realise reproducible test in pool. It was fitted with strain gauge at the ankle. 16 fins were tested for the two-foot morphologies. ANOVA test were used to discriminate the most influential parameters and define if they are the same for both morphologies. The most influential factor was the angle between the liner and the blade ($p<0,1$). Different morphologies induce different influence parameters.

KEYWORDS: freediving fins, experimental measurement, strain, ankle morphology.

INTRODUCTION: In order to increase the performance of a freediving fin, it is necessary to increase the lift and reduce the drag (Loebbecke et al., 2009). For this, several elements may need to vary: the rigidity of the blade (must be necessary to disrupt the flow and extract a propulsive force) (Luersen, 2004; Nicolas et al., 2010; Pendergast et al., 2003) , the surface of the blade (the drag and lift forces are proportional to it)(Loebbecke et al., 2009; Nicolas & Bideau, 2009; Zamparo et al., 2006), the presence of directional channels (to limit the quantity of water going to the sides and reducing drag) (Pelizzari, 2005), the angle of inclination between the blade and the liner to reduce muscular effort at the ankle (Pelizzari, 2005). In addition, kicking depends on the morphology (size, weight, joint mobility…) of the diver (Pelizzari, 2005). Valgus for example causes discomfort (specifically for women) in kicking induced by the friction of the fins together and therefore muscle pain (shin splints, cramps…) (Pelizzari, 2005). Changing the kicking also results in a less hydrodynamic position and therefore a reduction in performance (Gea-García et al., 2020). In order to limit the risk of injury, pain or even increase sport performance, it is important to know the forces applied by the fin on the freediver (these modify the diver's energy consumption). As the ankle is the first joint in contact with the fin, it will be strongly impacted. In order to determine these joint efforts, a prosthetic foot can be used (Collins & Kuo, 2010; Tryggvason et al., 2017) to avoid human-related constraints and lighten the test load imposed on freedivers. Preliminary studies have shown the need to have a foot as close as possible to reality in order to obtain consistent results. That's why a Poteor Dynastep prosthetic foot has been chosen to reproduce human movements. The Proteor Dynastep prosthetic foot allows, with its double blades, to reproduce flexion/extension and inversion/eversion movements. Thus, the objective of this work is to define which fin parameter has the most impact on the forces applied to the ankle depending on the morphology of the ankle. This will be a first step in helping freedivers choose their own fins regarding performance and preventing potential risks.

METHODS: To find out which factor has the most influence on the response or to know if the factors have an influence on each other, a complete experimental design has been put in place (Equixor, 2016; Goupy, 2006). Four parameters with two levels were selected from the most important in the literature: stiffness (a fin sold as very flexible and a fin as very rigid: the exact fin stiffness was measured by photogrammetry (Figure 1)), water channelling (with or without side rails), the angle between the blade and the liner (an angle of 5° and one of 35°) and the length of the fin (a short fin=55cm and a long fin=70cm).

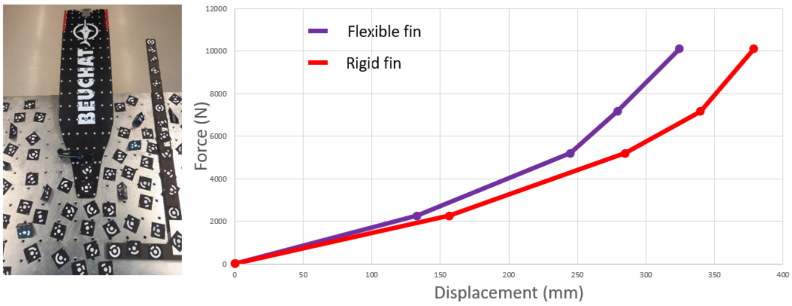


Figure 1: Definition of fin stiffness with photogrammetry

A total of 16 fins were tested according to the experiment matrix (Table 1). Each fin has been tested ten times. To determine the risk of pain or injury, we measured the forces applied to the ankle by the fin in X and Y directions.

Experiment matrix = fin configuration				
Tests to be performed				
Trial n°	Angle between the blade and the liner	Water pipe	Blade stiffness	Blade length
1	5°	Without side rails	Very flexible	Short blade
2	35°	Without side rails	Very flexible	Short blade
3	5°	With side rails	Very flexible	Short blade
4	35°	With side rails	Very flexible	Short blade
5	5°	Without side rails	Very rigid	Short blade
6	35°	Without side rails	Very rigid	Short blade
7	5°	With side rails	Very rigid	Short blade
8	35°	With side rails	Very rigid	Short blade
9	5°	Without side rails	Very flexible	Long blade
10	35°	Without side rails	Very flexible	Long blade
11	5°	With side rails	Very flexible	Long blade
12	35°	With side rails	Very flexible	Long blade
13	5°	Without side rails	Very rigid	Long blade
14	35°	Without side rails	Very rigid	Long blade
15	5°	With side rails	Very rigid	Long blade
16	35°	With side rails	Very rigid	Long blade

X maximal efforts (N)		
Fin configuration	Mean	Std
1	-0,9	0,022
2	-0,7	0,044
3	-0,9	0,0026
4	-1,4	0,031
5	-2,3	0,018
6	-2,2	0,056
7	-0,8	0,007
8	-0,6	0,022
9	-1	0,012
10	-0,8	0,012
11	-0,9	0,004
12	-0,8	0,009
13	-0,9	0,018
14	-1,8	0,034
15	-0,8	0,016
16	-0,6	0,009

Y maximal efforts (N)		
Fin configuration	Mean	Std
1	-0,5	0,08
2	-0,7	0,042
3	-0,5	0,05
4	-0,4	0,036
5	-0,3	0,17
6	-0,7	0,24
7	-0,6	0,08
8	-0,6	0,015
9	-0,3	0,042
10	-0,4	0,074
11	-0,5	0,083
12	-0,5	0,11
13	-0,4	0,011
14	-0,2	0,093
15	-0,6	0,02
16	-0,4	0,38

Table 1: Characteristics of the experimental design: experiment matrix for fin configuration (on the left) and ankle's effort measured for a healthy foot (on the right)

The fins were tested on the 3 DiVE (free Diving Valgus Experiment) rig (Figure 2 a) which is an instrumented Dynastep (a Proteor prosthetic foot). This makes it possible to best reproduce the movement of human feet (sagittal flexion range=6,70°; inversion/eversion angle=19,09°). The forces in X and Y directions of the ankle were recorded at a sample rate of 10Hz by Arduino using 2 full bridges (4 strain gauges each) (Figure 2 b). Data were filtered with a 2nd order Butterworth filter with a cut-off frequency of 15Hz in Matlab 2022.

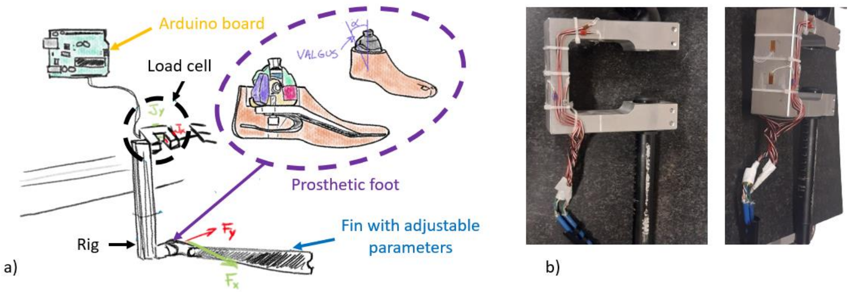
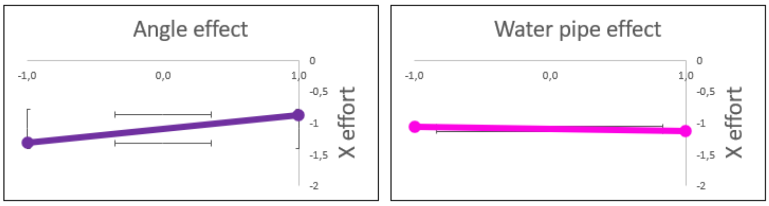


Figure 2: a) Description of the 3 DiVE rig: free diving fin with adjustable parameters, prosthetic foot with the possibility to make different morphologies, load cell to acquire strain on the ankle in X and Y direction b) zoom on the load cell.

The 3 DiVE was activated to move back and forth to reproduce ten kicking cycle (to take an average) in a swimming pool (kick frequency=0,6Hz with an amplitude of 0,5m)(Nicolas et al., 2010). This protocol was carried out for two different ankle configurations: for the foot without deformation and for the foot with a hallux valgus.
To find out statistically whether the means of the 4 parameters (four independent variables) were similar, a four-way factorial ANOVA test was conducted with R for X effort and another for Y effort (two dependent variables). Statistical significance was accepted at the $p<0,1$ level

for two factors interactions and main effects. These statistical analyses were carried out on the results obtained with the healthy foot as well as those obtained with the foot with valgus, to determine if the fin parameters involving the greatest forces were the same. In this way, we'll know if a diver needs a different fin (he has valgus or not).
Hexagon's Lunar software (an artificial intelligence software) was used to propose an optimised configuration. Linear interpolation was performed with the Kriging solver, which gives the lowest trial/modal error. Optimization was carried out with the Downhill algorithm to reduce ankle strain and thus increase performance. (*ODYSSEE*)

RESULTS: For a foot without deformation the results are the following. The greater the angle between the liner and the blade, the more the force in x and y will decrease (Figure 3). Increasing the rigidity of the fin leads to a significant increase in the forces on the ankle in x (2,2N for a rigid fin versus 0,9N for a flexible fin) but very low in y (0,7N for a rigid fin versus 0,5N for a flexible fin) (Table 1). The most influential factor for a foot without deformation is the angle between the liner and the blade and the stiffness of the blade (p=0,0797 and p=0,09819 respectively) (Figure 3). Thus, the experimental design made it possible to determine that there is a statistically significant interaction between the length and the stiffness (F=9,061 and p=0,017). There is no other significant interaction.



ANOVA for X effort		
Effect	F	p
Angle	3,7265	**0,0797**
Water pipe	0,0967	0,76161
Stiffness	3,3646	**0,09819**
Length	1,7685	0,21049

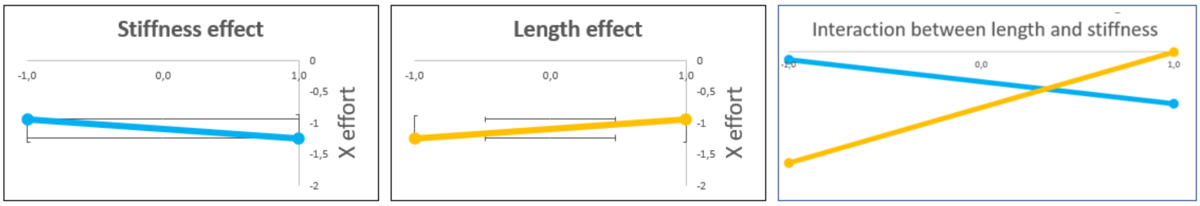


Figure 3: Effects of the different parameters on the X effort (on the left) and ANOVA results for X effort (on the right) (for a healthy foot).

For a foot with a valgus, results reveal that fin length is very influential (p=0,0874) as the stiffness. Angle between the blade and the liner, on the other hand has no significant influence.

DISCUSSION: The study of the forces made it possible to determine that they are not distributed in the same way depending on the morphology of the ankle. The results of the optimisation thanks to artificial intelligence made it possible to find a solution which reduces the forces at the ankle depending on two feet morphologies (with or without valgus). To minimise X effort, if the diver's foot is healthy, choose a fin with a wide angle, no water pipe and a long length. It would be interesting to test other foot morphologies/pathologies so that every freediver can find his own fin. An increase in stiffness and a decrease in fin length lead to an increase in ankle forces, which is consistent with the results found in the literature (Marion et al., 2010; Nicolas et al., 2010). In addition (Zamparo et al., 2002) have shown that a stiffer fin increases energy consumption. For the future, it will be interesting to carry out the same experimental plan but with real divers by putting them with muscular activity sensors as EMG (electromyography), body position sensors as IMU (Inertial Measurement Unit) or mask type sensors for oxygen saturation and see if ever the factors which have the most influence are the same regarding energy consumption. Comparison of the experimental design with divers and with the 3 DiVE would show the validity of the tool. When kicking, the two most important joints after the ankle are the hip and knee because they provide the propulsion force (Wojtków & Nikodem, 2017). So, having a fully articulated leg to have the forces at each joint and see the position when kicking would be “required”. Lastly, even if the 3 DiVE chosen is one that as close to reality, it still does not reproduce exactly the same movements as the real foot. But we can ask ourselves whether its reproducibility is sufficient. This could make it possible to completely avoid experiments with humans, which can be long and fastidious, and to only carry out experiments on a mechanical twin.

CONLUSION: This technique makes it possible to achieve effort without human influence. It promises to be a real benefit for coaches and athletes alike, finding a fin to suit two possible ankle configurations without overstraining divers. The use of artificial intelligence could be real advantage in finding the right balance between comfort and performance. Thus, depending on the result it will be possible to work differently on the fin and the personalized one.

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