

## THE ERGOPOD: A SIMPLE DEVICE TO MEASURE ON-SHORE WAVE ACTION

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### ABSTRACT

Wave action is one of the most important but, at the same time, one of the most difficult to quantify, of the many factors leading to the concept of 'exposure' on the shore. The ergopod measures water velocity indirectly and was developed to fulfil the requirement for a small, cheap instrument that was simple to construct and would give a physical value related to the water velocity and, hence, the wave action to which it was exposed. It is based on the principle that thicker wires require correspondingly greater forces (*i.e.* higher water velocities) to bend them. Details of construction are given. The dimensions are not critical, but those indicated give the size of the units on which the field and calibration trials were carried out. The device described here is both cheap and small. Its simplicity lends itself to multiple deployment in fieldwork. An example is given of its use investigating the effects of water velocities on mussel attachment forces.

### INTRODUCTION

WAVE ACTION is one of the most important but, at the same time, one of the most difficult to quantify, of the many factors leading to the concept of 'exposure' on the shore (Lewis, 1968). The effects of waves are related to their amplitudes and, while the fetch, the extent of the sea horizon, and the slope of the shore may be used as a yardstick to their potential (Thomas, 1986), these aspects ignore other topographical features which may enhance or reduce wave impact.

The wave battering received by littoral organisms arises from the complex of variable forces generated by water movement as it dissipates the energy released from each breaking wave. Biotic structures, separating incompressible water from entrained but compressible air, become subjugated to distorting forces as pressures wax and wane in turbulent flow. Shear and drag forces are induced, also, by moving water flowing over and around stationary or anchored forms. These forces increase proportionally with the square of the water velocity (Vogel, 1981) which, in turn, increases with wave amplitude. Water in the crest of a wave moves forward at the wave propagation velocity, which may be considerable for a large wave in deep water. A wave with a 10 second period travels at  $15\text{m}\cdot\text{s}^{-1}$  (Weigel, 1964). When approaching land, most ocean waves of this size and greater are influenced by decreasing depth at a considerable distance offshore and, by the time they reach shoal water in the offing, have broken down into smaller waves of shorter period and slower speeds. All waves are affected by the rising sea bed, and the increased drag it causes. Eventually, an instability occurs when the steepening crest, moving more rapidly than the water below, falls forward as either a spilling or a plunging wave. The resulting water movement on the shore must be similar to that in the breaking wave, perhaps less than in the bigger waves observed at sea, but Carstens (1968) suggests that a 10m high plunging breaker may strike the beach at about  $14\text{m}\cdot\text{s}^{-1}$ . Considerable transient pressures have been predicted (and also recorded) when, at a critical stage in the instability, a wave breaks onto or against a relatively flat surface, trapping a thin layer of air. It is at this moment, too, that the greatest

forces have been recorded on shore structures. The combination of these high, but transient, pressures with lower, but longer acting, hydrostatic pressures, arising from wave height and momentum, has the potential to produce a driving force capable of accelerating some of the water to greater velocities. Certain topographical features may channel and enhance this process, as may trapped and compressed air as it expands. Plumes of water thrown skywards at such times are a common sight and the simple laws of dynamics dictate that a plume ascending to 30m, an extreme but by no means exceptional example in heavy seas, must have been ejected at a velocity of about  $24\text{m}\cdot\text{s}^{-1}$ .

High transient pressures are unlikely to have an appreciable effect on the shore biota, due to the organisms' essentially fluid content and, hence, incompressible nature. Where gas spaces do occur, the flexibility of most tissues suggests that damage will be minimal. Damage is more likely from the drag forces experienced in fast-moving water; forces that increase with the size of the organism and with the square of water velocity. Velocities of extreme magnitude may be relatively infrequent, but their importance in determining survival on the shore is likely to be considerable. This view has been expressed also by Jones and Demetropoulos (1968), Denny (1983) and Vogel (1981), the last suggesting that water velocities up to  $17\text{m}\cdot\text{s}^{-1}$  may not be uncommon.

Wave heights may be estimated, but the difficulty of measuring water velocity in the littoral zone stems from its magnitude, the forces exerted, and the consequent requirement for robust equipment—coupled with the practical problems of installation, deterioration or loss in a harsh and corrosive environment. The sophistication, and expense, of accurate recording equipment also precludes replication, to any great extent; a particular drawback in fieldwork. Simple systems have been developed, however, and, although limited in extent, they are nonetheless valuable. Slow offshore currents have been measured using leachable plaster (Muus, 1968; Doty, 1971), while wave-impact effects have been compared, successfully, using a nail, spring clip and metal plate (Harger, 1970). Drogue plates, attached to spring balances, have recorded swash energy on sand (Schiffman, 1965) and on rock (Jones & Demetropoulos, 1968). A more sophisticated simple dynamometer, capable of recording both the direction and the magnitude of the forces experienced by sessile organisms, was described by Denny (1983). All these devices rely on detecting, and measuring, the forces induced by water movement—the prime factor of wave exposure.

The ergopod also measures water velocity indirectly and was developed to fulfil the requirement for a small, cheap instrument that was simple to construct and would give a physical value related to the water velocity and, hence, the wave action to which it was exposed. It is based on the principle that thicker wires require correspondingly greater forces (*i.e.* higher water velocities) to bend them. In common with the impact and drogue dynamometers, mentioned above, the observed values indicate maxima over any one tidal immersion, but these are of great value as a complement to other physical features when comparing biological indicators of exposure.

The instrument, and its calibration, are described; and an example of its use is presented, in which water velocities were estimated at two adjacent locations of differing aspect and were compared with a biological indicator—the anchor strengths of the mussel, *Mytilus edulis*.

## MATERIALS AND METHODS

### Construction

The device is shown in Fig. 1. The dimensions are not critical, but those indicated below give the size of the units on which the field and calibration trials were carried out. The

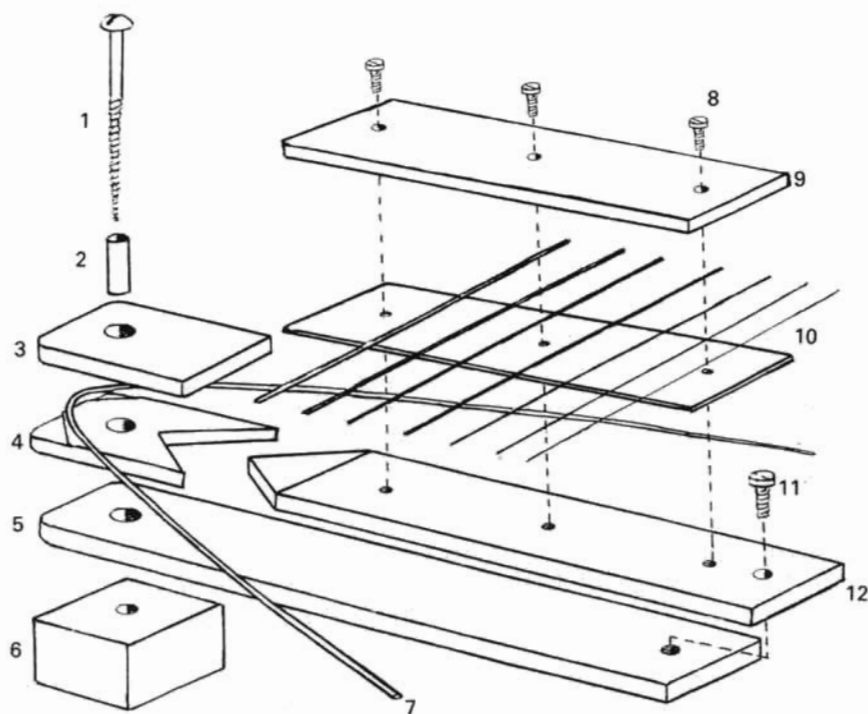


FIG. 1.

An exploded diagram of the component parts of the ergopod. 1 - fastening screw; 2 - sleeve; 3, 4 and 5 - cemented together to form the base; 6 - mounting block; 7 - deflecting wire, or 'antennae'; 8 - 2BA brass machine screws; 9 - upper layer of the wire-bearing portion; 10 - foam strip and indicating wires; 11 - 0BA brass machine screw; 12 - lower layer of the wire-bearing portion.

component parts were made from perspex sheet, 3mm thick, cut first into strips 25mm wide. From these strips, a 175mm length was cut to form the base (5). A similar length, divided with cuts commencing 48mm from one end, and directed at 45° into this shorter end, formed parts 4 and 12. Lengths of 48mm and 100mm formed parts 3 and 9 respectively. Parts 3, 4 and 5 were cemented together, with the ends flush and part 4 in the middle, so that its 'V' cut formed a socket opening onto the adjacent surface of the base (5). A perpendicular hole, 6.5mm in diameter, was drilled through these cemented parts, on the centre line and 10mm from the end. The triangular point of part 12 was reduced slightly in thickness so that, when laid along the base, it would fit easily into the 'V' socket. When in this position, a pilot hole was drilled on the centre line, at about 9mm from its square end, through both this part (12) and the base (5). The lower part of the hole through the base was tapped 0BA and the upper end, in part 12, opened out to clear 0BA. A brass 0BA cheese-head machine screw (11) was inserted to hold these two together. With part 12 thus located, the 100mm length (9) was clamped on top, abutting the top layer of the block (3), but allowing a small clearance of about 0.5mm, or the thickness of thin card. Three pilot holes were drilled through this part (9) into the strip (12) below, taking care not to enter the base (5). These holes were all located on the centre line, one in the middle and the other two 8mm from either end of the 100mm length (9). They were tapped 2BA through the lower layer (12) and widened to clear this screw size in the top piece (9). Finally, to protect the metering wires from drifting flotsam, deflecting 'antennae', formed from a 300mm length

TABLE 1.  
Wire diameters, cross sectional areas and typical data

Wire diameter (mm)	Cross-sectional area $\times 10^{-3} \text{ mm}^2$	Data Example			
		score		score $\times$ area	
		left	right	left	right
0.56	246.00	1	1	246.0	246.0
0.40	126.00	2	3	252.0	378.0
0.28	61.60	3	3	184.8	184.8
0.20	31.40	3	4	94.2	125.6
0.14	15.40	3	4	46.2	61.6
0.10	7.85	5	5	39.3	39.3
0.07	3.96	5	5	19.8	19.8
		Totals		882.3	1055.1 mTsu
		mean		969 mTsu	

Equivalent maximum water velocity =  $12 \text{ m.s}^{-1}$   
Derived from  $0.53 (969^{0.45})$  (see expression (1) in the Discussion)

of 2.5mm diameter galvanised wire (7) were fitted to the base. The wire was bent at the centre to  $90^\circ$ , heated here, and drawn into a semicircular saw cut made round the middle (part 4) of the thick end of the base. As a result, the wire projected backward, on either side, at about  $45^\circ$  to the unit.

The ergopodia (or the functional part of the ergopod) consisted of a series of copper wires (Kewsol, grade 2, Kent Electrical Wire) sandwiched between the two upper layers (9 and 12). The wires were chosen to have cross-sectional areas which decreased in a geometric series from the front to the rear of the unit (Table 1). To ensure a firm grip, a thin foam strip  $100\text{mm} \times 25\text{mm}$  and about 1mm thick (10), was included with the wires between the perspex layers. The strip (10) was cut from a block of polyurethane foam of the type used commonly in the building industry for thermal insulation. Any similar firm, but yielding, material should suffice for this purpose.

The ergopodia were most easily assembled in a jig made to take the tongued strip (12). The polyurethane foam strip was laid on top and the wires laid perpendicularly across so that they projected more than 30mm on either side. The wires were arranged with the thickest nearest the pointed end. They were held firmly embedded in the polyurethane foam by the 100mm strip (9) fastened in place over them with the three short 2BA screws (8). When secured, the wire ends were trimmed so that they projected 30mm on either side of the sandwich and were bent to at least  $45^\circ$  and straightened 5 times by hand before use (see Discussion).

The component parts were cut and drilled carefully to the same dimensions, on a jig made for the purpose, so that, when in use on the shore, the assembled parts (9, 10 and 12) bearing the indicating wires could be made up separately and were interchangeable on site between unit bases.

### Deployment

On the shore, the base was fastened to a suitable substratum with a 3mm diameter round-headed screw (1) passing through a sleeve (2) and mounting block (6). The 20mm long sleeve (2) was cut from brass tubing having an external diameter of 6mm and an internal diameter of about 4mm. This was a loose fit in, and slightly longer than the 6.5mm hole in the base and, when firmly fastened to a substratum, allowed the unit to swing around it.

The screw length depended, to some extent, on the thickness of the block (6) which, in turn, depended on the surface irregularities over which the unit must be free to swing. Distancing blocks made from scrap iron, perspex or other plastic have all been used successfully. A convenient size, suitable for most surfaces, was a cube with a side of about 20mm, or a short length of rod of similar dimension, having a 3.5mm hole through the centre (axially through the rod) to take the fastening screw. The screw thus passed through the brass sleeve (2), through the base (5), through the distance piece (6) and into a secure substratum. A washer was occasionally required under the screw head if this was small or, with continued use, the hole through the perspex had enlarged through wear. Water on its own was an adequate lubricant, normally, but, in rough conditions, suspended sand had an abrasive effect.

When the screw was turned down tight against the brass tube, the ergopod was free to pivot around the sleeve and was held above the substratum by the distance piece. On most shores, the local rock provided a good anchor point. All but the most intractable rock could be drilled with a masonry bit, and a plug inserted to take the screw. Alternatively, but requiring more preparation, a plug set into quick-setting cement may be used. On other sites a wooden stake may suffice. The plane in which the ergopod pivoted was immaterial; the device was equally effective under an overhang as on a vertical or horizontal surface. It must pivot freely, however, as any impedance to its acting as a vane, and following the water flow, greatly increases the rate of work-hardening of the ergopodia. Local algal fronds, which could entangle the devices, were removed as were projecting organisms close enough to impede the swing.

The unit was fastened in place before the chosen site was covered by the incoming tide, and was inspected when uncovered after high water. Each wire was scored in one of six categories:-

Score	Definition
0	not bent
1	slightly bent
2	more bent but to less than 45°
3	bent to 45°, or a little more
4	well bent
5	completely bent, parallel (or nearly so) with the support

These categories correspond to 15° intervals and could be fairly closely judged by eye on site although some subjectivity was unavoidable. The score for each wire was multiplied by its cross-sectional area, and the resulting values summed to give two totals (Tsu values)\*, one for each side of the ergopod. An example is given in Table 1, in which the cross sectional areas have been multiplied by 1,000 to give a final value in mTs. After scoring, the wires were straightened, or a new set substituted by exchanging the wire-bearing portion, and the unit left to be immersed again by the following high tide.

Data analysis was carried out using generalised linear models (GLIM, Royal Statistical Society, 1985).

## RESULTS

### Calibration

Calibration tests were carried out in two flumes, one having a maximum and non-turbulent flow rate of  $2.5\text{m.s}^{-1}$ , in which wires alone were exposed, and the other with a maximum

\*Tsu = Tsunami.

TABLE 2.

Regression co-efficients for  $y^{0.45} = ax$  from wires exposed to water flows of up to  $2.5\text{m.s}^{-1}$ . The intercepts for the best fit regressions did not differ significantly from zero ( $P > 0.01$ ), hence the equations have been fitted through the origin

Source	n	a	standard error
New wires	26	4.39 <sup>a</sup>	0.0839
After 5 bending cycles	21	3.99 <sup>b</sup>	0.1000
After 40 bending cycles	24	3.63 <sup>c</sup>	0.0792
After 40 bending cycles	26	3.50 <sup>c</sup>	0.0794

Coefficients with dissimilar suffices are significantly different from one another ( $P < 0.001$ ).

greater than  $12\text{m.s}^{-1}$ , in which complete ergopod units were assessed. At the lower flow ranges, six wires with diameters between 0.4mm and 0.05mm were positioned in a row across the water flow, each projecting 30mm vertically above the flume bed into the water channel. Scores were recorded from sets of these wires, at a series of increasing water velocities, after which the wires were bent to at least  $45^\circ$  and straightened 5 times by hand, and exposures repeated. Two further series of exposures followed after 15 and 20 more bending cycles to give a series of wire responses after being bent and straightened 0, 5, 20 and 40 times.

The resulting plots of wire response to water velocity clearly formed a non-linear trend. Various transformations and equations were fitted and the pooled deviances were found to be least with wire response raised to the power of 0.45. The data were transformed, thus, for analysis of deviance which showed that pre-bending had a significant effect ( $P < 0.005$ ) on the wires' responses. The intercepts of the best fit regressions were not significantly different from zero ( $P > 0.1$ ), hence equations of the form  $y = ax^{0.45}$  were fitted and these are given in Table 2.

Complete ergopods were exposed in the faster flume. Here, the flows were non-turbulent up to about  $5\text{m.s}^{-1}$  and, although the presence of the ergopod itself disrupted the flow over the wires to some extent, this situation closely mimicked that occurring on the shore. At velocities above  $5\text{m.s}^{-1}$ , the flow became turbulent and began to fragment but, even so, continued to approximate closely to the conditions to be found in the swash of breaking waves. These higher velocities were recorded as mean values derived from the head of water feeding the flume. The wires used in these tests ranged in diameter from 0.56mm to 0.071mm and were exposed first without bending and, again, after 40 hand bending cycles applied as before.

Another series of exposures were made in this flume with ergopods that had been exposed previously on the shore, one set over three tidal cycles and another over five. The wires on these ergopods were deliberately not renewed between tides and, at the end of the sequence, some of the thinner wires were missing. Analysis of the results showed that pre-bending and tidal immersion had a significant effect ( $P < 0.005$ ). From the regressions given in Table 3, it is evident that the responses from these, though similar, all differed from the response of new wires. The lower coefficients from ergopods exposed previously on the shore were accentuated by the loss, during later tidal immersions, of some of the thinner wires, which resulted in disproportionately low scores at low water velocities.

TABLE 3.  
Regression co-efficients for  $y^{0.45} = a + bx$  from wires held in ergopods  
exposed to water flows of up to  $12\text{m.s}^{-1}$ .  $y$  in mTsu;  $x$  in  $\text{m.s}^{-1}$ .

Source	n	a	b	standard error
New wires	80	0*	2.07*	0.0267
After 40 bending cycles	44	0*	1.81 <sup>b</sup>	0.0331
After 3 tidal cycles	48	0*	1.77 <sup>b</sup>	0.0335
After 5 tidal cycles	58	-2.29	1.97 <sup>ab</sup>	0.1179

\*The intercepts are not significantly different from zero ( $P > 0.1$ ) and the equations have been fitted through the origin. Coefficients with dissimilar suffices are significantly different from one another ( $P < 0.001$ ).

Evidence for this effect was demonstrated by the best fit regressions. The intercept for ergopods immersed over five tidal cycles was the lowest, and was significantly different from zero ( $P < 0.05$ ). The intercept for the ergopods immersed over three tidal cycles was lower than that for those with hand bent or new wires, although none of these was significantly different from any other, or from zero ( $P > 0.05$ ).

Overall, the results from both flumes showed that bending caused a small, but significant, difference in the wires' responses and, although these differences were less subsequently, the responses continued to decline until the wires were close to fracture. Preliminary tests had shown that the thickest wire used, 0.56mm diameter, took more than 40 bends, to  $60^\circ$  and back, before fracturing, and the thinner ones many more.

### Field Tests

Ergopods have been exposed successfully over a wide range of conditions and in a number of situations. One comparison, which illustrates their potential, was recorded at two sites, about 20 meters apart, at mid tide level on an exposed NW-facing shore in Cornwall (Grid Reference SW 686477). The profile of this shore is inset in Fig. 2. Beyond the seaward site, the shore sloped gradually to low water, with no obstructions to reduce the full effect of waves breaking there. The landward site was protected, to some extent, by its slope, the seaward site and the creviced rocks between. The whole area was covered with a barnacle/mussel mosaic, typifying the exposed nature of this shore. Two ergopods were mounted at each site, and were scored, reset or renewed after each of the next four high tides. At each site, during the period of the experiment, the force of attachment and the length of individual mussels within 0.5m of the ergopods were measured (Price, 1982).

The relationships between anchor force and mussel length are shown in Fig. 2. As might be anticipated, the anchor force increased significantly with mussel size but, despite the considerable overlap evident from the standard error bars, analysis of deviance showed the increase to be significantly greater ( $P < 0.001$ ) at the seaward site. It was at this site, too, where the higher ergopod scores were recorded, indicating the greater water velocities experienced here.

### DISCUSSION

The results from the flume experiments show that the units responded well over the wide range of water velocities tested. The scores decreased with repeated bending and resetting;

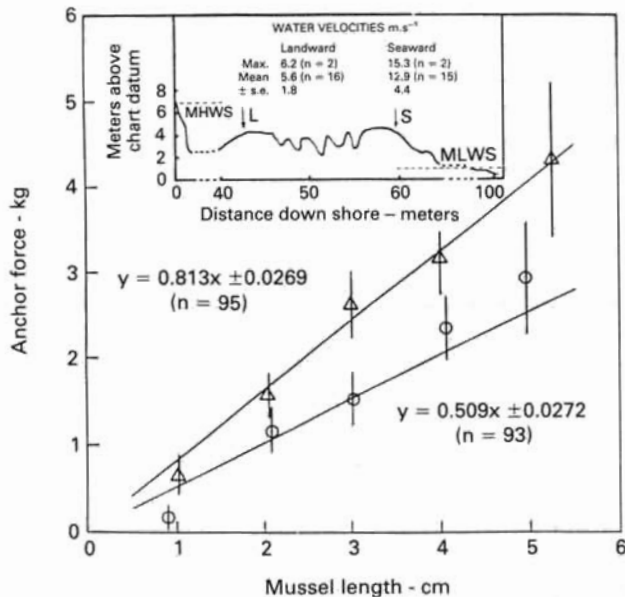


FIG. 2.

Mean attachment force, and standard errors, for mussels in a range of size classes on a landward (L,  $\circ$ - $\circ$ ) and a seaward (S,  $\triangle$ - $\triangle$ ) site. The intercepts of the best fit regressions were not significantly different from zero or one another ( $P > 0.1$ ), hence the regressions given have been fitted through the origin. The coefficients of these and the best fit equations both differed significantly between sites ( $P < 0.001$ ). Inset: Shore profile and wave velocities recorded at the two sites over four consecutive tidal cycles ( $n$  = a single observation from one side of one ergopod).

the differences being greatest initially (Table 2). Because the differences between work-hardened wires and those in their original state were slight, attempts to standardise the hardening process before assembly were abandoned. It was easier to work-harden the wires after assembly, by bending them at least five times to  $45^\circ$  before use. Because the wires took more than 40 bends to  $60^\circ$ , and back, before fracturing, it was feasible to use the same wires over a number of tidal cycles. In practice, fracture of the thicker (less easily bent) wires did not occur and the thinner wires normally survived more than one tidal cycle, except in rough conditions. Thus, it would seem legitimate, when wires are broken, to score the spaces similarly to the next wire up in the series; the procedure adopted here.

However, ergopods which have been exposed to rough conditions (high velocities) should not be used, subsequently, in less severe conditions (low velocities). The thinner wires, well worked, previously, by turbulent water may break, or give misleading scores when rigidity is lost just before fracture. Thin wire integrity is vital when measuring low velocities, whereas their scores contribute little when water velocities are high. An example of the errors incurred by this sequence may be seen from inspection of the data in Table 1. If the three (or four) thinnest wires are removed on both sides, and scored as the next wire up in the series, the final scores are diminished by 2% and (5%) respectively. Whereas, in slower water movement, scores of 1 for the 0.28mm wires and 0 for the thicker ones would cause under estimates of 8% and 58% respectively. It was for this reason that the ergopods exposed previously to five tidal cycles, and missing some of their thinner wires, gave readings too low when exposed to low velocities, resulting in an intercept significantly different from zero (Table 3).



The coefficient of the expression

$$\text{velocity} = 0.53 (\text{mTsu}^{0.45}) \dots\dots (1)$$

chosen for evaluating water velocities on the shore, was interpolated from the results achieved by ergopods in the fast flume, based on the pattern of hardening found in the slow flume. Thus, although the coefficient after 5 bending cycles was significantly different from that after 40 cycles (Table 2), a value midway between these embraced, with its confidence interval, the range of values likely to be experienced on the shore. Graphical interpretation of the regression coefficients in relation to bend cycles reveals this value to be less than the new wire coefficient by a factor 0.72 times the difference between new wires and those close to fracture (40 bend cycles). For the slower flume, this coefficient was 3.75, derived from:-

$$4.39 - (0.72 (4.39 - 3.50)) = 3.75 \dots\dots (2)$$

The equivalent coefficient from the fast flume data, and the one used for converting mTsu values from the shore to  $\text{m.s}^{-1}$  was 1.88 giving:-

$$\text{mTsu}^{0.45} = 1.88 \times \text{velocity} (\text{m.s}^{-1}) \dots\dots(3)$$

equivalent to the expression given above (1). The coefficients were lower in the fast flume, probably because each wire, although experiencing mainly turbulent flow, was in the wake of the next one up in the series, as well as that of the deflecting 'antennae'; and might have been influenced, also, by the boundary flow near the ergopod. The exponent used in the expression serves to linearise the data and minimise errors which, for the 95% confidence interval, were calculated to lie within 5% of the estimate.

Values derived from exposures on the shore may also be influenced by flotsam and by detached algal fronds. The likelihood of false readings arising in this way must be dependant on the nature of the surroundings and the amounts of drifting algae, which increase during and after storms. False values were usually obvious from a complete flattening and twisting of most, or all, of the wires, giving extreme scores on one or both sides of the unit. Usually, values from each side of an ergopod were in fairly close agreement. When large discrepancies occurred, the high values were ignored. In practice only about 5% of the readings were suspect.

Caution should be exercised when extrapolating to velocities greater than those used in these experiments. Although best fitting relationships were obtained with the algorithm given, and yielded correlation coefficients of 0.92 and better, there was a small discontinuity in the data from the fast flume at the point where the flow became turbulent. This discontinuity was small enough to be ignored over the range of flows tested but analysis of the data, from the turbulent flow alone, suggests that extrapolation to higher velocities, using the relationship given above (1), may under estimate true water velocities around  $20\text{m.s}^{-1}$  by about 10%. Considering the accuracy of the device, this discrepancy is well within acceptable limits for the velocities normally experienced on most shores.

The experiment which included data from ergopods and mussels provides one interesting example of how knowledge of local wave action may enhance a study of features exhibited by the biota. Mussels have been shown to fasten themselves to the substratum more strongly in winter than in summer, presumably a response to the more severe battering received in that season. This response to strong wave action occurs with little, or no,

time lag but decays slowly during periods of weak wave action (Price, 1982). The waves experienced on this occasion were large, although not exceptionally so, and were accompanied by a big swell. Water velocities indicated by the ergopods were high also, particularly at the more exposed site, and serve to confirm the values that have been estimated from the forces exerted by water movement in the swash of big waves (Vogel, 1981; Denny, 1983). The mussels reflect this trend, being more firmly attached at the more exposed site.

Lewis (1968) has indicated that quantitative correlations between wave action and distribution of the biota, particularly of the key species which may be used to indicate degrees of exposure (Ballantine, 1961), may be inappropriate due to the dynamic and fluctuating nature of the habitat. Studies with similar aims to that described above, relating water velocity measurements to other variables such as algal frond structure, local topography and the nature of down-shore and off-shore topography, can be most instructive. The device described here is both cheap and small. [It could be reduced even further in size, though different wire lengths would require recalibrating]. It is suitable for investigating the effects of features having a local influence. Its simplicity lends itself to multiple deployment in fieldwork and, although equally as susceptible as other dynamometers to the 'gefingerpockengrockel', it is less obvious than more complex instrumentation, thus reducing the likelihood of unauthorised tampering.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

- BALLANTINE, W. J., (1961). A biologically-defined exposure scale for the comparative description of rocky shores. *Field Studies*, **1** (5), 1-19.
- CARSTENS, T., (1968). Wave forces on boundaries and submerged bodies. *Sarsia*, **34**, 37-60.
- DENNY, M. W., (1983). A simple device for measuring the maximum force exerted on intertidal organisms. *Limnology and Oceanography*, **28**, 1269-1274.
- DOTY, M. S., (1971). Measurement of water movement in reference to benthic algal growth. *Botanica Marina*, **14**, 32-35.
- HARGER, J. R. E., (1970). The effect of wave impact on some aspects of the biology of sea mussels. *Veliger*, **12**, 401-414.
- JONES, W. E. and DEMETROPOULOS, A., (1968). Exposure to wave action: Measurements of an important ecological parameter on rocky shores on Anglesey. *Journal of experimental marine Biology and Ecology*, **2**, 46-63.
- LEWIS, J. R., (1968). Water movements and their role in rocky shore ecology. *Sarsia*, **34**, 13-36.
- MUUS, B. J., (1968). A field method for measuring 'exposure' by means of plaster balls. *Sarsia*, **34**, 61-68.
- PRICE, H. A., (1982). An analysis of factors determining seasonal variation in the byssal attachment strength of *Mytilus edulis*. *Journal of the Marine Biological Association, U.K.*, **32**, 147-155.
- SCHIFFMAN, A., (1965). Energy measurements in the swash-surf zone. *Limnology and Oceanography*, **10**, 255-260.
- THOMAS, M. L. H., (1986). A physically driven exposure index for marine shorelines. *Ophelia*, **25**, 1-13.
- VOGEL, S., (1981). *Life in moving fluids* Willard Grant Press, Boston Mass. 352pp.
- WEIGEL, R. L., (1964). *Oceanographical Engineering*. Prentice Hall, New York. 532pp.

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(or a plea for the next evolutionary step?)

The phylogenetic relationships of ergopodids are obscure. When observed submerged on the shore, the gross morphology and bilateral symmetry shows a weak affinity with that of the Trilobitomorpha, but the link is tenuous and does not stand up to close scrutiny. They have diverged, also, from the Flotsoplasticata, having a greater skeletal density, and thus form a closer link with the Methacrylinae - and the Jetsoplasticata in general. This is an unfortunate but, seemingly, logical classification until further research uncovers a homing mechanism for those errant individuals which develop the migratory urge.