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# Friction RandomPOD—A new method for friction measurement in noncyclic, multidirectional, dynamic pin-on-disk tests for orthopaedic bearing materials

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## Abstract

The 16-station, computer-controlled RandomPOD wear test device was re-designed into a friction measurement device, Friction RandomPOD. The motion was implemented by a servo-electric x-y-stage and the load was proportional-pneumatic. The direction of sliding, velocity ($v$), acceleration, and the magnitude of the load ($L$) varied randomly and continuously. The nominal contact pressure $p$ varied between 0 and 2.4 MPa and $v$ between 0 and 40 mm/s. In the first version of the device, the frictional force components were continuously measured by two miniature load cells in two perpendicular directions. In the second version, the measurement was done with a three-axial, commercial load cell. The resultant frictional force was divided by the instantaneous load in order to obtain the coefficient of friction ($\mu$) at a frequency of 200 Hz. Due to the light and accurate design of the device, vibrations were absent in the measured signals although the measurements were most dynamic. Hence no filtering was needed. Serum lubricated polyethylene/CoCr tests revealed non-symmetric distributions of $\mu$, friction power $P_{\mu}$, and $\mu$ vs. $pv$.

Keywords: orthopaedic tribology; noncyclic pin-on-disk; dynamic friction measurement; servo-drive; extensively cross-linked UHMWPE

# 1. Introduction

In orthopaedic tribology, noncyclic tests have been introduced (Saikko and Kostamo, 2011) in order to avoid possible unrealistic phenomena due to strictly cyclic tests (ISO 14242-1) that do not reflect the high biomechanical variability of everyday activities (Bergmann et al., 2001; Bennett et al., 2008; Halilaj et al., 2018; Lunn et al., 2019). With the 16-station RandomPOD, it has been found that noncyclic tests produce higher wear factors compared with cyclic test conditions (Saikko and Kostamo, 2011). This is likely to be mainly caused by the increased multidirectionality of the relative motion which is a dominant factor in the polyethylene wear (Calonius and Saikko, 2003). In the circularly translating pin-on-disk device, CTPOD (Saikko, 1998), the direction of sliding changes 360°/s relative to the polyethylene pin, whereas in the RandomPOD, the corresponding figure is 500°/s although the mean sliding velocity, 15.7 mm/s, is only half of that in the CTPOD, 31.4 mm/s. In RandomPOD testing, multidirectionality together with serum lubrication have been shown to result in clinically relevant wear mechanisms regarding both the total hip and total knee prostheses by using flat-on-flat and ball-on-flat contacts, respectively (Saikko and Kostamo, 2011; Saikko, 2014; Saikko et al., 2015). The principal features that must be reproduced are the so-called adhesive polishing topography and wear particles of the realistic submicron size and shape (McKellop et al., 1995; Bragdon et al., 1996; Wang et al., 1996; Jasty et al., 1997; Saikko, 1998; Edidin et al., 2001; Pourzal et al., 2016). The RandomPOD is, however, a pure wear test device. Therefore, the friction in the highly dynamic RandomPOD test conditions remained unknown. To correct this deficiency, a Friction RandomPOD was designed and built on the RandomPOD frame. Two different friction measurement arrangements were tested. From the frictional force measurements, the coefficient of friction, $\mu$, was computed at a frequency of 200 Hz. The first test results for the $\mu$, frictional power $P_\mu$ and $\mu$ vs. $pv$ distributions are reported and discussed.

## 2. Materials and methods

The 16-station, computer-controlled RandomPOD wear test device has been described in detail elsewhere (Saikko and Kostamo, 2011). In brief, the relative motion consisted of two translations so that the random slide track remained within a circle of 10 mm diameter, the average change of the direction of sliding was 500°/s, and the maximum acceleration was 300 mm/s$^2$. The load $L$ varied randomly between zero and 150 N. In the present study, the device was transformed into a friction measurement device, the Friction RandomPOD. The servo systems were updated, but the motion and load were unchanged. Two different designs were used as follows.

**Version 1, the four-station Friction RandomPOD.** On the motion plate, four additional, miniature $x$-$y$-stages were constructed using linear bearings (Figs. 1a to 1c). The test disk was fixed on top of the miniature $x$-$y$-stage assembly, i.e., on the upper piece of rail. The motion of the disk relative to the motion plate was prevented by two calibrated miniature load cells that thus measured the frictional forces, $F_{\mu x}$ and $F_{\mu y}$ in two perpendicular directions. The load cells were of 'button' type designed for compression only. They were a part of a miniature subassembly similar to that described in (Saikko, 1998). $L$ was measured with a force transducer (HBM U9C 200 N) fixed to the piston rod of a pneumatic cylinder (load actuator).

**Version 2, the single-station Friction RandomPOD.** On the motion plate, a three-axial load cell (Forsentek MAC 200 N) was fixed (Figs. 1d and 1e). With the load cell, $F_{\mu x}$ and $F_{\mu y}$ and $L$ were measured.

In both versions, the resultant, $F_\mu = (F_{\mu x}^2 + F_{\mu y}^2)^{0.5}$, was divided by the instantaneous $L$, and so the coefficient of friction $\mu$ was obtained at a frequency of 200 Hz (Fig. 2). With small $L$ values, $\mu$ naturally becomes uncertain. Therefore, $\mu$ values obtained with small $L$ values, below 5 N or 10 N, were excluded. The distributions of $v$ and $L$ are shown in Fig. 3. The friction power $P_\mu$ was defined as $F_\mu v$. The cylindrical pins had a diameter of 9.0 mm and length of 12 mm. The nominal contact pressure $p$ was $L$ divided by the cross-section area of the pin, 63.6 $mm^2$. Hence, $p$ varied between 0 and 2.4 MPa. The product $pv$ (Fig. 3) is often used in the studies of plastic bearings (Lancaster, 1971). $\mu$ vs. $pv$ was readily computed.

The pins were made from vitamin E stabilized (0.1 % blended), extensively cross-linked (100 kGy gamma-irradiation dose) ultra-high molecular weight polyethylene (UHMWPE, ASTM F648, ISO 5834-1,2, ASTM F2695, ASTM F2565), hereafter VEXLPE, as described in detail elsewhere (Saikko, 2019). The disks were polished CoCr (ISO 5832-12) with a surface roughness $R_a$ value of 0.01 $\mu$m (Saikko, 2019). The lubricant was HyClone alpha calf serum SH30212 diluted 1:1 with deionized water. The protein concentration of the lubricant was 20 mg/ml. The lubricant bulk temperature was kept at 20 °C in order to retard microbial growth and protein denaturation. The lubricant chambers were surrounded by a water bath, from which water was sucked by a peristaltic pump and circulated through a Peltier type cooler/heater back to the bath. The inlet and outlet pipes were not in contact with the friction assembly to avoid measurement errors.

The duration of version 1 test was 1 week. Before the test reported in the present paper, several weeks of tests were run to fine-tune the friction assemblies and to run the pins in so that the wear faces were quite polished at the start of the present test. The test specimens and conditions in the 4 test stations were as similar as possible, so that no differences between them were observed in scrutiny, regarding for example the dimensions of the manufactured parts, that could be assumed to lead to substantial variation in the results. With version 2, the same pins and disks were used. With three of these pin/disk couples, a 1 week RandomPOD test and a 1 week CTPOD test were performed. Hence, the version 2 test programme took 6 weeks to complete. In a CTPOD test, the pin translated along a circular track of 10 mm diameter at a constant velocity of 31.4 mm/s and the load was constant 71 N (Saikko, 1998). The CTPOD conditions were programmed to the Friction RandomPOD in order to make comparison with the results from the established CTPOD device (Saikko, 1998; Saikko, 2019) possible. In this way, the novel Friction RandomPOD could be validated against the established CTPOD device. The wear was evaluated gravimetrically (Saikko, 2019).

## 3. Results

All measured signals were free from vibrations and therefore no filtering was needed. With version 1, the mode $\mu$ values were 0.102, 0.084, 0.082 and 0.092 (Fig. 4), and the wear factor of the pins was $1.65 \pm 0.26 \times 10^{-6}$ $mm^3/Nm$. The variation of friction among the four test stations could not be eliminated although the one week test was repeated several times. With version 2, the mode $\mu$ values in the three RandomPOD tests were 0.099, 0.103 and 0.102, and the mode $\mu$ values in the three CTPOD tests were 0.310, 0.343 and 0.333. The wear factors were $1.61 \pm 0.14 \times 10^{-6}$ $mm^3/Nm$ and $0.55 \pm 0.22 \times 10^{-6}$ $mm^3/Nm$ in the RandomPOD and CTPOD tests, respectively. In all tests, the average weight loss of the pins was 1 mg/week.

The $F_\mu$, $\mu$, and $P_\mu$ distributions were non-symmetric (Fig. 4). The $L$ cutoffs of 5 N and 10 N resulted in similar $\mu$ modes. During the 7-day test, $\mu$ showed a slightly increasing trend (Fig. 5). The $\mu$ vs. $pv$ plots show that in the most typical $pv$ range of 0.5 to $3.5 \times 10^4$ N/ms, $\mu$ was mostly between 0.05 and 0.25, and there was a decreasing trend of $\mu$ with increasing $pv$ (Fig. 6).

## 4. Discussion

A novel friction measurement pin-on-disk system was designed for non-cyclic, multidirectional, dynamically loaded tests for orthopaedic bearing materials. Distributions of $F_\mu$, $\mu$, $P_\mu$ and $\mu$ vs. $pv$, unprecedented in their non-symmetrical shape, were produced from 120 million measurements per test in each test station. The one week test duration in friction measurement could be considered a long term test. In version 1, there was variation of friction among the test stations (Fig. 4), the extent of which left room for some improvement. The variation may have been caused by slight jamming in the shaft/bores (Fig. 1(c)), although they were precision reamed to a clearance of 0.01 mm. Therefore, version 2 was implemented. The repeatability of the friction results with version 2 was considered satisfactory.

The present dynamic $\mu$ values with a mode of 0.1 were less than half of those obtained with constant $p$ (1.1 MPa) and $v$ (31.4 mm/s) using the CTPOD device, 0.20 to 0.25 (Saikko, 2019). This is logical since as $p$ changes continually, the chances of lubricant ingress are improved. The $\mu$ values with constant $p$ and $v$ therefore may be considered conservative, worst case values. The CTPOD $\mu$ values with version 2 (mode 0.31 to 0.34) were even higher than those obtained with the actual CTPOD device. This was likely to be attributable to the fact that the test duration in the present study was one week, whereas the CTPOD measurements were of 30 min duration (Saikko, 2019). Regarding the wear, this was the first study to compare the VEXLPE wear in the RandomPOD vs. CTPOD test conditions in the same test device. The RandomPOD wear factor was 2.9-fold higher. With conventional UHMWPE, the corresponding ratio was 1.8 (Saikko and Kostamo, 2011). The fact that the ratio was higher than unity was likely to be attributable to the increased multidirectionality of the RandomPOD.

Multidirectional POD studies, in which friction and wear are studied simultaneously, from other research groups are scarce in literature. With a multidirectional 'OrthoPOD' device (two rotations), Wimmer et al. (2013) measured $\mu$ values mostly around 0.06 with a static $p$ value of 3 MPa for UHMWPE against polished CoCr in serum, that is, not far from the present values. Similarly, with a multidirectional POD device (one translation, one rotation), Cowie et al. (2019) obtained an average $\mu$ value of 0.07 with static $p$ value of 3 MPa for UHMWPE against polished CoCr in serum.

There are plenty of serum lubricated unidirectional (pin against a unidirectionally rotating disk) and reciprocating (pin against a reciprocating disk) POD papers in literature for orthopaedic bearing materials. However, these studies can presently be considered irrelevant in state-of-the-art orthopaedic tribology since only multidirectional tests can reproduce the clinical wear mechanisms (McKellop et al., 1995; Wang et al., 1996; Bragdon et al., 1996; Saikko, 1998). It is logical and reasonable to assume that the same holds true for the friction behavior (Kaddick et al., 2015; Haider et al, 2016; Sonntag et al., 2017). Uniaxial grooving and other uniaxial wear marks typical of unidirectional and reciprocating tests are likely to strongly affect wear and friction. Uniaxial grooving is never seen on the bearing surfaces of retrieved prosthetic components (Jasty et al., 1997; Edidin et al., 2001; Pourzal et al., 2016). Unidirectional and reciprocating studies are still published despite the fundamental research work done and published on the multidirectionality issue in the 1990s regarding wear and in the 2010s regarding friction. It can even be stated that in the present day uniaxial and reciprocating studies for implant bearing materials, the state of the art in orthopaedic tribology is neglected.

In a multidirectional hip simulator friction and wear simultaneous study with dynamic load, Haider et al. (2016) obtained a friction factor (which corresponds to the friction coefficient in POD tests) of $0.070 \pm 0.0045$ for polished, 40 mm CoCr femoral heads against VEXLPE acetabular cups. This range is close to the $\mu$ values measured in the present study. This indicated that with a multidirectional motion and a dynamic load a POD device can produce $\mu$ values quite comparable with those produced by a full-scale hip simulator. However, the conspicuous non-symmetric shape of the $\mu$ distribution (Fig. 4) implicated that mean and standard deviation should not be used to describe the distribution of $\mu$.

The relatively low wear indicated that the present *pv* values were in a safe region. It was not the intention in the present study to define any *pv* limit for VEXLPE wear in a multidirectional, serum-lubricated test. Instead, the idea was to simply study the variation of $\mu$ with thermal intensity that varied continually and randomly. The observation that $\mu$ decreased with increasing *pv* (Fig. 6) was in agreement with (Wang, et al., 2017) in which it was found that $\mu$ decreased with increasing $p$ and $v$ that were tested separately (UHMWPE against AISI 52100 steel, $R_a$ = 0.1 µm, dry and water lubricated).


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## Conflict of interest statement

The authors have nothing to declare.

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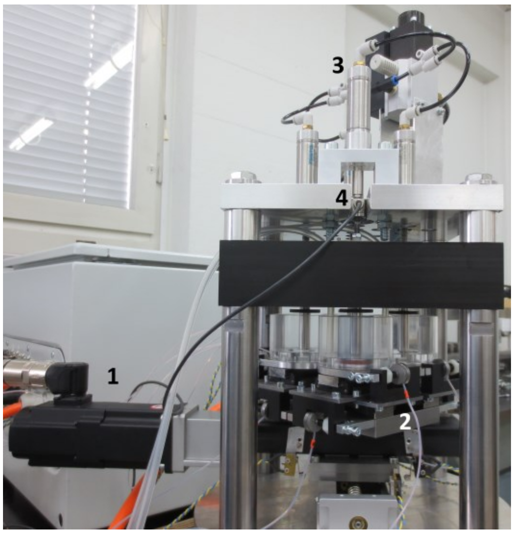


Figure 1(a). Version 1 Friction RandomPOD; 1 servo drives, 2 motion plate, 3 pneumatic load actuators, 4 force transducer for *L* measurement.

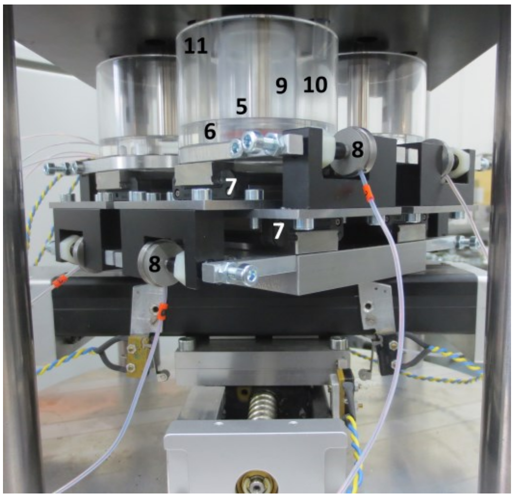


Figure 1(b). Friction measurent assembly, 5 pin, 6 disk, 7 linear bearing, 8 button load cell, 9 lubricant chamber, 10 water bath, 11 hose for circulating cooling/heating water.

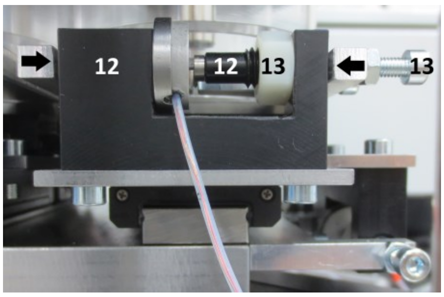


Figure 1(c). Subassembly for button load cell, 12 shaft/bore, 13 play removal screw. Arrows indicate directions of frictional force.

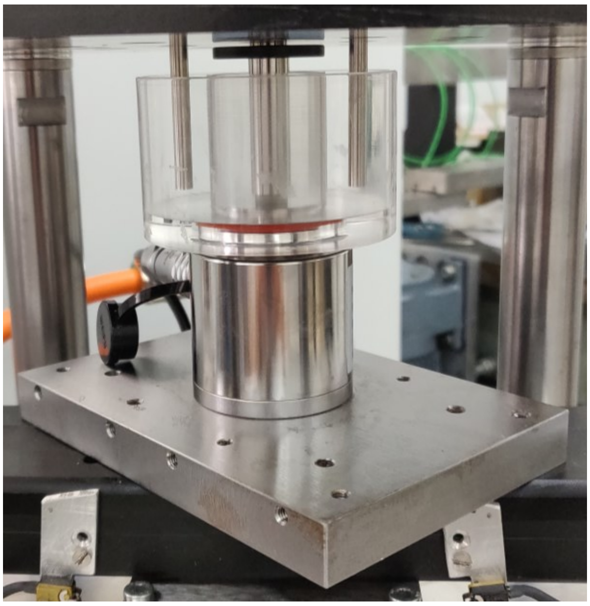

Figure 1(d). Version 2 Friction RandomPOD; three-axial load cell was an alternative way to measure $F_{\mu x}$ and $F_{\mu y}$ and $L$.


Figure 1(e). Checking version 2 calibration in $x$ direction with 30 N load.

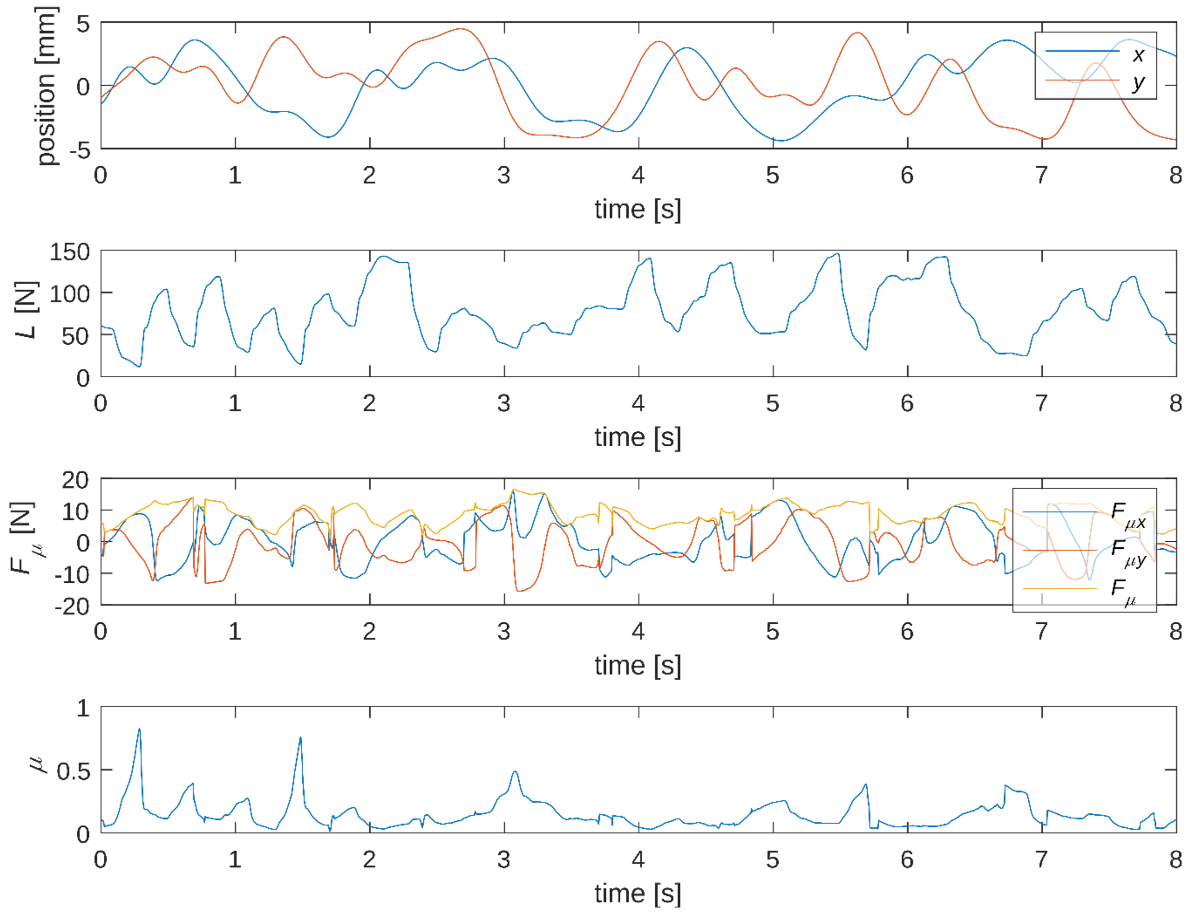


Figure 2. Example of variation of $x$ and $y$ coordinates, $L$, $F_{\mu x}$, $F_{\mu y}$, $F_{\mu}$ and $\mu$ during 8 s in version 2 Friction RandomPOD test.

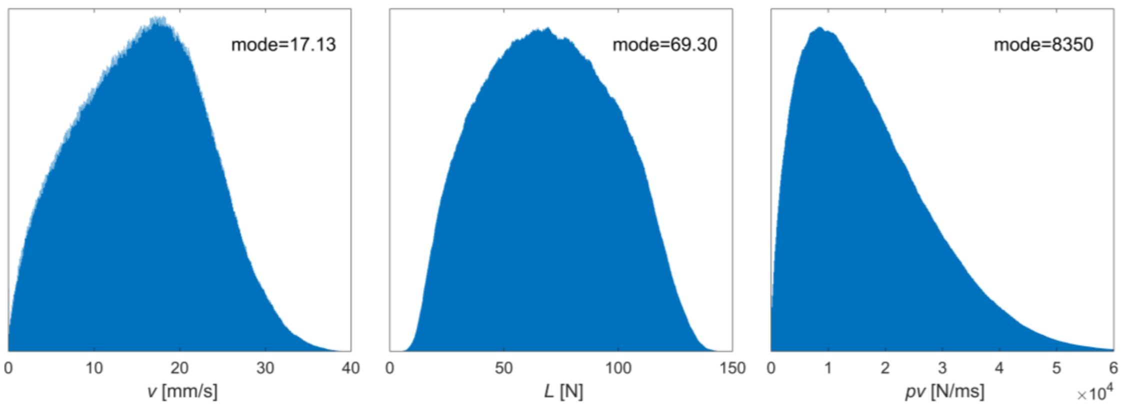


Figure 3. $v$, $L$ and $pv$ distributions in version 2 Friction RandomPOD test.

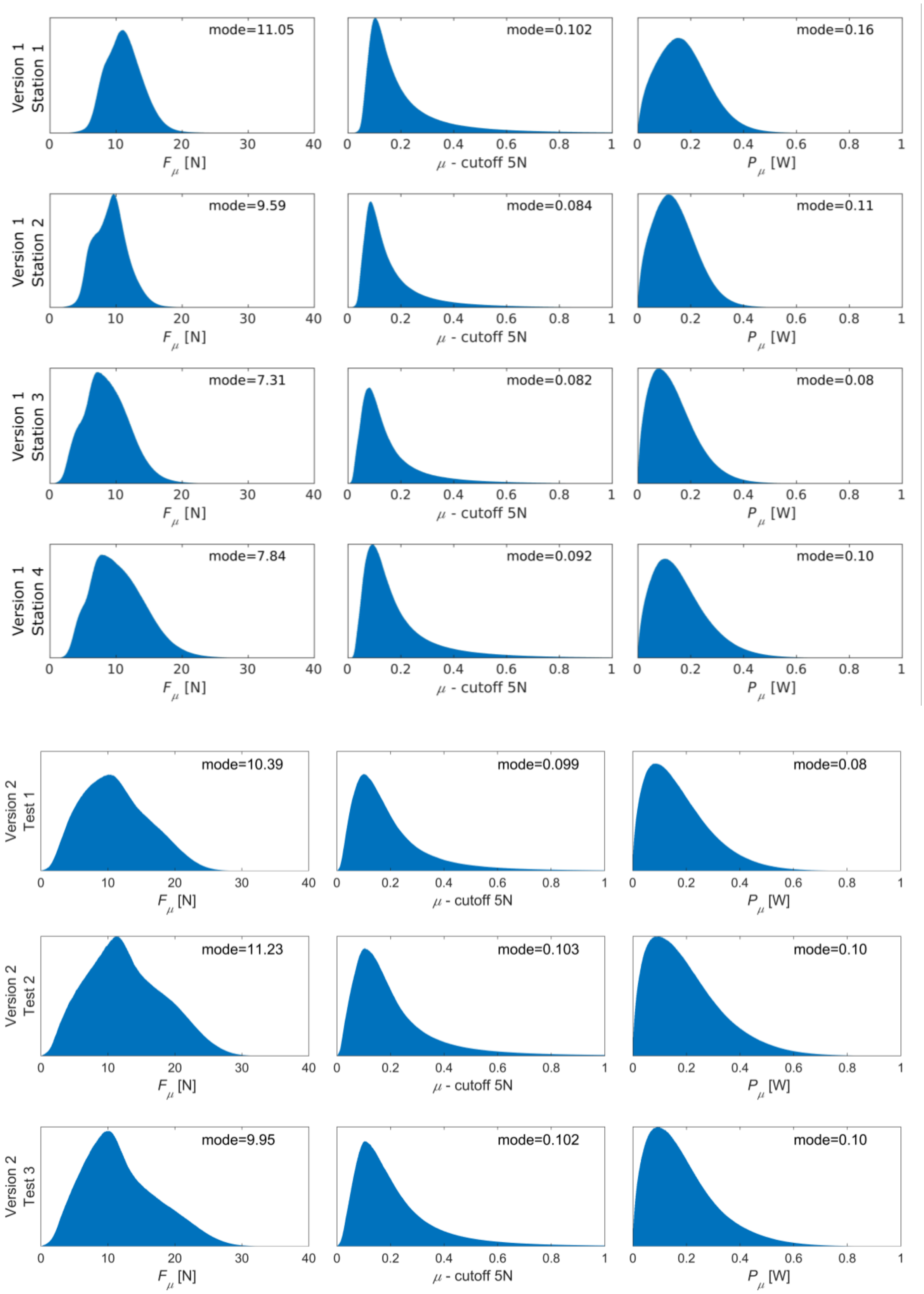


Figure 4. $F_\mu$, $\mu$, and $P_\mu$ distributions in version 1 and 2 Friction RandomPOD tests.

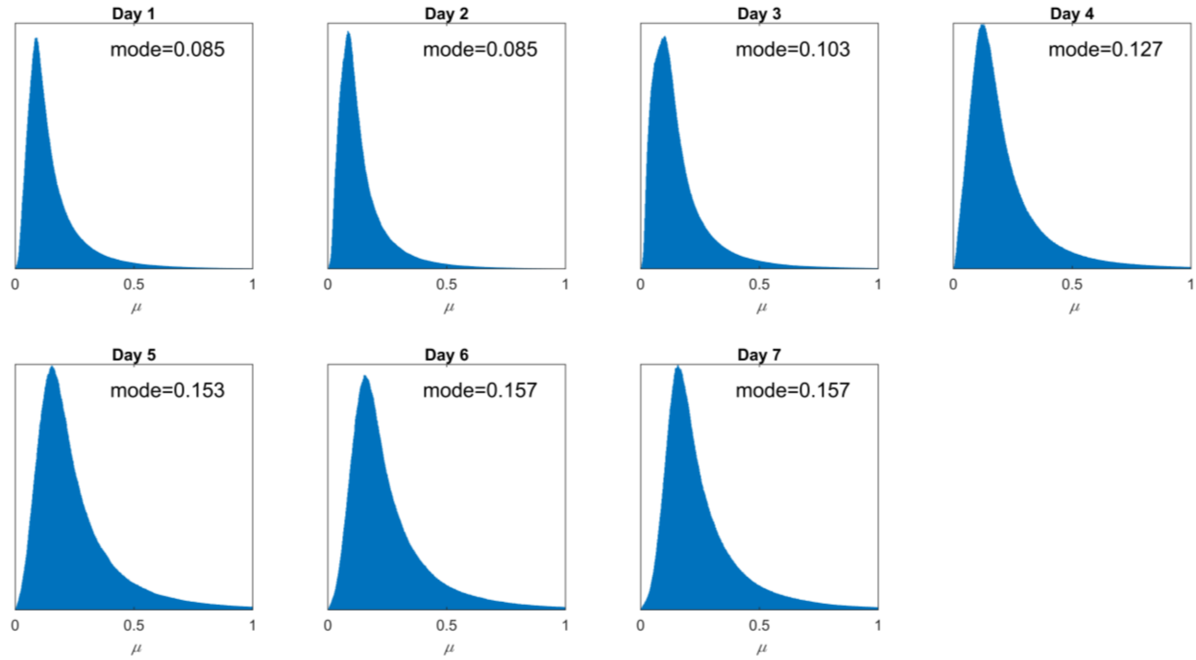


Figure 5. Evolution of $\mu$ in one of version 2 Friction RandomPOD tests.

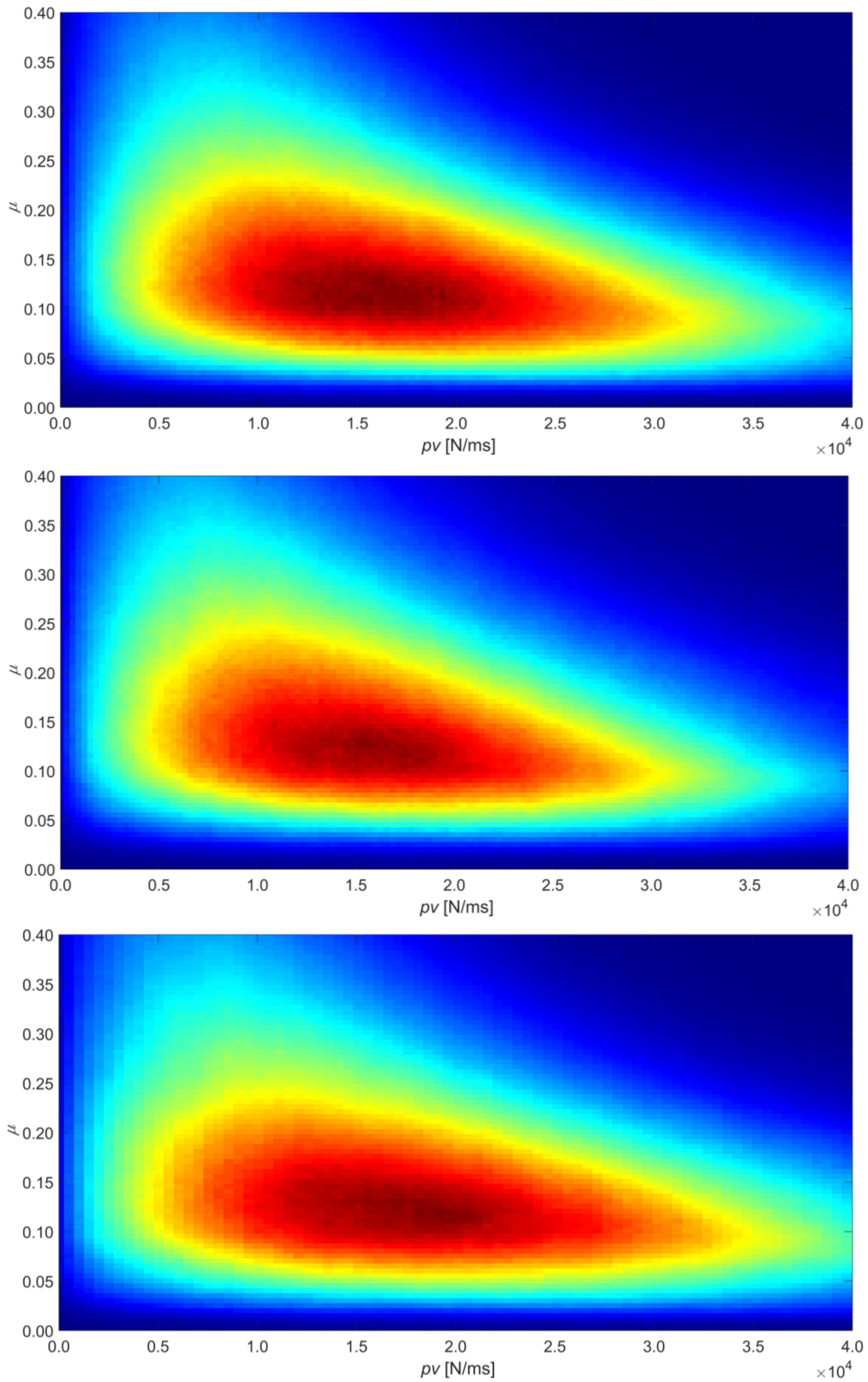


Figure 6. Color maps of $\mu$ vs. $pv$ in three version 2 Friction RandomPOD tests. Dark red indicates the densest concentration $\mu$-$pv$ pairs of values, and dark blue the thinnest.